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# THE MANGANESE OXIDE MINERALS: A PRELIMINARY REPORT.[1]

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ABSTRACT.

This paper summarizes the results obtained thus far in an intensive study of the manganese oxide minerals. X-ray powder photographs, supplemented by chemical tests, have proved to be the best means for identifying these minerals. Formulas are suggested. Physical properties and X-ray data are listed for the commoner minerals and those for which new data have been obtained. Rules of nomenclature for these minerals are suggested.

## INTRODUCTION.

AN intensive study of the so-called "manganese oxide" minerals was undertaken early in 1941 by the Chemical Laboratory of the U. S. Geological Survey as part of the strategic minerals studies of manganese ore deposits. It was hoped that X-ray and optical study would make possible the selection of homogeneous material for chemical analysis and thermal study, and that by a correlation of all these methods, the discrepancies and contradictions in the literature concerning these minerals could be explained and reconciled.

The results attained have demonstrated that these minerals can be differentiated and identified. The X-ray powder photograph method has proved to be the most effective method for this work, especially when supplemented by simple chemical tests. Optical study by reflected light as yet has proved to be of less value, chiefly

[1] Published by permission of the Director, Geological Survey, U. S. Department of the Interior.

because many samples are so fine-grained that they are apparently isotropic, hence are indistinguishable when examined by reflected light. Such samples have commonly been reported in the literature as amorphous. X-ray study shows that nearly all of these apparently isotropic specimens are crystalline. Over two hundred X-ray powder photographs of these minerals have been taken in the Geological Survey laboratory. About 90 per cent of the samples were identified by means of their pictures; about 5 per cent gave good pictures which have not yet been correlated with known minerals; and less than 5 per cent gave pictures so weak as to be unidentifiable. As it is now possible to identify the minerals present in manganese ore deposits with reasonable certainty, the primary objective of the work is accomplished. At the same time, progress has been made towards an understanding of the chemical compositions of the manganese oxide minerals, of their optical properties, and of their behavior when heated. Nevertheless, many problems remain to be solved and it is probable that some time will elapse before details can be completed and final publication will be possible. Published references [2] to this project have elicited requests for further information. It seems desirable, therefore, to present at this time a summary of the results, some of which are tentative and subject to revision.

## PURITY OF MATERIAL STUDIED.

Specimens apparently homogeneous under the binocular microscope are X-rayed and a polished surface is examined by reflected light. If no inhomogeneity is revealed, a sample is prepared for analysis and the final preparation is again X-rayed. Even so, the chemical analysis does not necessarily give the true composition of the pure mineral. Two possible sources of error remain:

(1) A crystalline admixture may be present in a percentage too small to be detected by the X-ray powder pattern. The percentage

[2] Richmond, W. E., and Fleischer, Michael: Ranciéite, a valid mineral species. Abs., Am. Min. 27: 231, 1942.

Richmond, W. E., and Fleischer, Michael: Cryptomelane, a new name for the commonest of the "psilomelane" minerals. Am. Min. 27: 607–610, 1942.

of crystalline admixture which may escape detection is not known for mixtures of the manganese oxide minerals, but may well be appreciable, because of the similarities in the powder pictures of some of them.

(2) Amorphous material, which gives no X-ray powder picture, may be present, in small or large amount. Thus, for example, in an intergrowth of 50 per cent very fine-grained cryptomelane and 50 per cent amorphous material, both materials might appear to be isotropic; the sample might appear to be homogeneous by reflected light, would give the X-ray pattern of cryptomelane, and yet might have a composition markedly different from that of pure cryptomelane.

These possible sources of error may be the explanation of the divergence in composition found for some samples. The analysis of a number of samples, selected with the precautions stated above, should give a reasonably good approach to the chemical composition of the pure minerals.

## NOMENCLATURE.

The nomenclature of the manganese oxide minerals has been in an unsatisfactory state, chiefly because the term "psilomelane" has come to be used to refer to any hard, massive, unidentified manganese oxide mineral. This usage is doubtless convenient in the field, where it is generally impossible to determine the mineral or minerals present, and some collective term is needed. However, as stated below, the term "psilomelane" should not be used in this sense, but should refer to only one of the several distinct minerals hitherto grouped under this designation.

The following rules of nomenclature are recommended:

(1) Massive, hard, heavy material not specifically identified should be referred to as belonging to the "psilomelane type." This term is to be understood to include several distinct minerals or mixtures of them, and no chemical formula should be given.

(2) Massive, soft material of low apparent specific gravity, not examined in the laboratory, should be referred to as "wad." Such

material also may be any one of several distinct minerals, may be a mixture, or may be unidentifiable and no chemical formula should be given.

(3) Definitely identified minerals should be named as listed below.

## MINERALOGY OF THE MANGANESE OXIDES.

The following list includes all the recognized manganese oxide minerals with the exception of a few very rare species and some of doubtful validity. The formulas marked (?) are new and subject to revision. The four minerals marked with asterisks are by far the most common, judging by the specimens studied in this laboratory.

Bixbyite—$(Mn, Fe)_2O_3$.
*Braunite—$3(Mn, Fe)_2O_3 \cdot MnSiO_3$.
Cesarolite—$Pb\ Mn_3O_7 \cdot H_2O$. Rare.
Chalcophanite—$(Mn, Zn)Mn_2O_5 \cdot 2H_2O$. Rare.
Coronadite—$Pb\ R_8O_{16}$(?), $R = Mn^{IV}$ chiefly, also $Mn^{II}$, Cu, Zn.
Crednerite—$Cu\ Mn_2O_4$. Rare.
*Cryptomelane—$KR_8O_{16}$(?), $R = Mn^{IV}$ chiefly, also $Mn^{II}$, Zn, Co.
Galaxite—$(Mn^{II}, Fe^{II})(Al, Fe^{III})_2O_4$. Rare.
Hausmannite—$MnMn_2O_4$.
Hetaerolite—$ZnMn_2O_4$.
Hollandite—$BaR_8O_{16}$(?), $R = Mn^{IV}$ chiefly, also $Fe^{III}$, $Mn^{II}$, Co.
Jacobsite—$(Mn^{II}, Fe^{II}, Mg)(Mn^{III}, Fe^{III})_2O_4$.
Lithiophorite—$Li_2(Mn^{II}, Co, Ni)_2Al_8Mn^{IV}_{10}O_{35} \cdot 14H_2O$(?).
Manganite—$MnO(OH) = Mn_2O_3 \cdot H_2O$.
Manganosite—$MnO$. Rare.
Polianite = Pyrolusite. The name polianite should be dropped.
*Psilomelane—$BaR_9O_{18} \cdot 2H_2O$(?), $R = Mn^{IV}$ chiefly, also $Mn^{II}$, Co.
Pyrochroite—$Mn(OH)_2$. Rare.
*Pyrolusite—$MnO_2$.
Quenselite—$Pb_2Mn_2O_5 \cdot H_2O$. Rare.
Ramsdellite—$MnO_2$ (dimorph of pyrolusite).
Ranciéite—$(Ca, Mn^{II})\ Mn^{IV}_4O_9 \cdot 3H_2O$(?).
Sitaparite = Bixbyite.[3] The name sitaparite should be dropped.

More detailed descriptions of the commoner minerals and of those for which new data have been obtained are given below.

[3] Mason, Brian: Bixbyite from Långban. The identity of sitaparite with bixbyite. Geol. For. Forh. (Stockholm) 64: 117–125, 1942.

*Braunite*—$3(Mn, Fe)_2O_3 \cdot MnSiO_3$. Tetragonal. Color and streak dark brownish-black. Hardness 6–6½. Sp. gr. 4.8. Occurs in well developed crystals resembling octahedrons and in compact granular masses. Common in the United States. Decomposed by HCl, leaving a residue of gelatinous silica.

*Coronadite*[4]—$PbR_8O_{16}$ (?), R = $Mn^{IV}$ chiefly, also $Mn^{II}$, Cu, Zn. This formula is obtained by analogy to the formulas of hollandite and of cryptomelane, which give almost identical X-ray powder photographs. The analyses of coronadite agree only approximately with this formula. Most samples contain 1–5 per cent of non-essential water. Probably triclinic, pseudotetragonal. Color steel-gray to dull black. Streak black. Hardness 6. Sp. gr. 5.2–5.6. Occurs in irregular or cellular or botryoidal masses. The validity of coronadite as a mineral species was recently demonstrated by Frondel and Heinrich.[5]

*Cryptomelane*—$KR_8O_{16}$ (?), R = $Mn^{IV}$ chiefly, also $Mn^{II}$, Zn, Co. Most samples contain 2–4 per cent non-essential water. Most of the analyses correspond fairly well to this formula, but some differ considerably from it. A satisfactory explanation for these discrepancies has not yet been found. Tetragonal. Color steel-gray to black, tarnishes black. Streak dark brownish-black. Hardness most commonly 6–6½, but the apparent hardness of cleavable and fibrous varieties may be as low as 1. Sp. gr. approximately 4.3.

Cryptomelane is probably the commonest of these minerals excepting pyrolusite. It occurs in a number of habits:

(1) Most commonly as very fine-grained steel-gray dense compact masses showing marked conchoidal fracture.

(2) Less commonly as botryoidal masses.

(3) Uncommonly as coarse cleavage masses that would not ordinarily be labelled "psilomelane type." This variety has an

[4] A paper on coronadite is in preparation by Dr. Clifford Frondel of Harvard University and Dr. Charles Milton of the Geological Survey, to whom we are indebted for the use of their data. They are not to be held responsible, however, for the formula here proposed.

[5] Frondel, Clifford and Heinrich, E. W.: New data on hetaerolite, hydrohetaerolite, coronadite and hollandite. Am. Min. 27: 48–56, 1942.

apparent hardness of 3–4. Known only from Tombstone, Arizona, Deming, New Mexico, and Sitapur, India.

(4) As distinct crystals. Known only from Romanèche, France, where the crystals occur on massive psilomelane. Specimens from Tombstone, Arizona, and Lake Valley, New Mexico, show filament-like fibers of cryptomelane. Similar material from Nassau, Germany, has been described by Ramsdell.[6]

Cryptomelane was first distinguished as a distinct mineral species by Ramsdell,[7] who referred to it as "true psilomelane." The name cryptomelane was recently proposed by us.[8]

*Hausmannite*—$MnMn_2O_4$. Tetragonal. Color brownish-black to reddish. Streak reddish-brown. Hardness 5–5½. Sp. gr. 4.9. Occurs in well developed crystals resembling octahedrons, and in granular masses. Commonly twinned.

*Hollandite*—$BaR_8O_{16}$ (?), R = $Mn^{IV}$ chiefly, also $Fe^{III}$, $Mn^{II}$, Co. Usually anhydrous, but may contain a little non-essential water. A partial solid solution series between hollandite and cryptomelane exists, but the limit of isomorphous replacement is not known. Probably triclinic, pseudotetragonal. Color silvery-gray to dull black. Streak black. Hardness 6 in most specimens, but the apparent hardness may be as low as 2. Sp. gr. 4.5–5.0. Occurs as well developed crystals, broad cleavage masses, dense compact masses with conchoidal fracture, or as botryoidal masses.

The statement, frequently made in the literature, that hollandite is the crystalline equivalent of colloidal or amorphous psilomelane is incorrect. X-ray study shows that both minerals are crystalline and distinct, though closely related. Dehydration of psilomelane at 500–600° C. gives hollandite as the chief product.

*Lithiophorite*—$Li_2(Mn^{II}, Co, Ni)_2Al_8Mn^{IV}_{10}O_{35}\cdot 14H_2O$(?). Color dull black, commonly with a distinct bluish tinge (mark of high cobalt content) particularly noticeable on fresh fracture. Streak black. Sp. gr. 3.1. Commonly in botryoidal masses.

[6] Ramsdell, L. S.: An X-ray study of psilomelane and wad. Am. Min. 17: 143–149, 1932; Ramsdell, L. S.: The unit cell of cryptomelane. Am. Min. 27: 611–613, 1942.

[7] Ramsdell, L. S.: op. cit., p. 144.

[8] Richmond, W. E. and Fleischer, Michael: op. cit., p. 607.

Lithiophorite is listed in most textbooks as a variety of psilomelane. Ramsdell [9] found that it gave a distinctive X-ray powder photograph. The validity of lithiophorite as an independent species has been confirmed by us.

*Manganite*—$MnO(OH)$. Monoclinic; pseudo-orthorhombic. Color dark steel-gray to iron-black. Streak chocolate-brown. Hardness 4. Sp. gr. 4.3. Occurs in prismatic crystals. Commonly partly altered to pyrolusite.

*Psilomelane*—$BaR_9O_{18}\cdot 2H_2O(?)$, $R = Mn^{IV}$ chiefly, also $Mn^{II}$, Co. The water is essential (difference from hollandite, whose composition is very similar). Orthorhombic. Color and streak black. Hardness usually 6, but in some specimens the apparent hardness is lower, down to 2. Sp. gr. 4.4–4.7. A common mineral; only pyrolusite and cryptomelane are encountered more frequently. Most commonly in botryoidal masses, which in some instances consist of concentric layers. The layers may be psilomelane, psilomelane and pyrolusite, or psilomelane and cryptomelane. Also occurs in irregular or cellular masses, and rarely as long prismatic crystals (pseudomorphs ?) resembling a common variety of pyrolusite.

X-ray and chemical studies of type specimens by Vaux [10] proved that the mineral named psilomelane by Haidinger [11] is a distinct species, a hydrous barium manganate. Our X-ray study and new chemical analyses confirm Vaux's findings. The formula here given is a variant of that proposed by Vaux, $R_2Mn_8O_{18}\cdot 2H_2O$, $R = Ba$, $Mn^{II}$. The name psilomelane should be used only to refer to this particular mineral; unidentified material should be referred to as "psilomelane type."

*Pyrolusite*—$MnO_2$, commonly with a little non-essential water. Tetragonal. Color iron-gray to black. Streak dead black. Hardness nearly always 2–2½, but in some specimens higher, up

[9] Ramsdell, L. S.: op. cit., p. 145.

[10] Vaux, George: X-ray studies on pyrolusite (including polianite) and psilomelane. Min. Mag. 24: 521–526, 1937.

[11] Haidinger, William: Mineralogical account of the ores of manganese. Royal. Soc. Edinburgh Trans. 11: 119–174, 1831.

to 6½. Sp. gr. 4.9–5.0 pure, 4.7–4.8 for most specimens. The commonest manganese oxide mineral, occurring in several habits:

(1) Compact, fine-grained, dense masses with a tendency to fracture conchoidally.

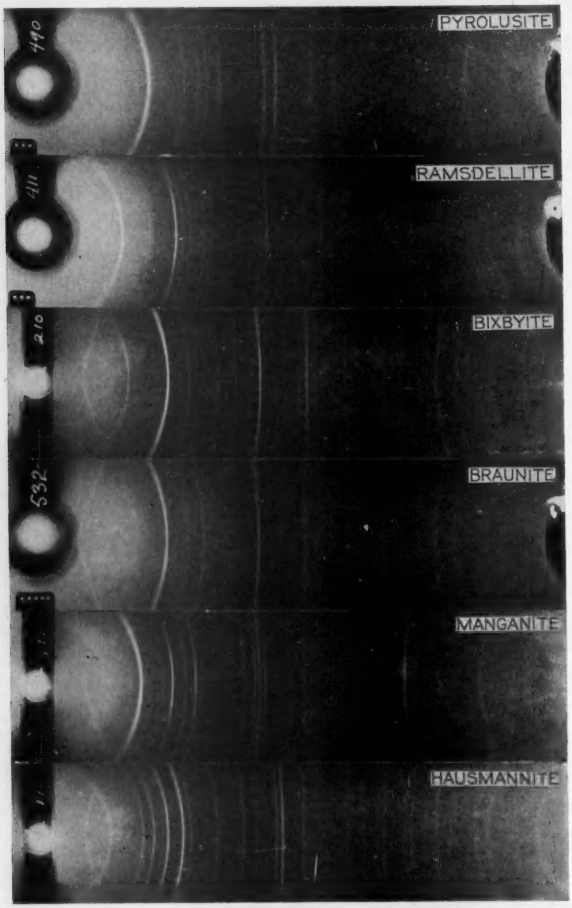



FIG. 1. X-ray powder photographs of some manganese minerals.

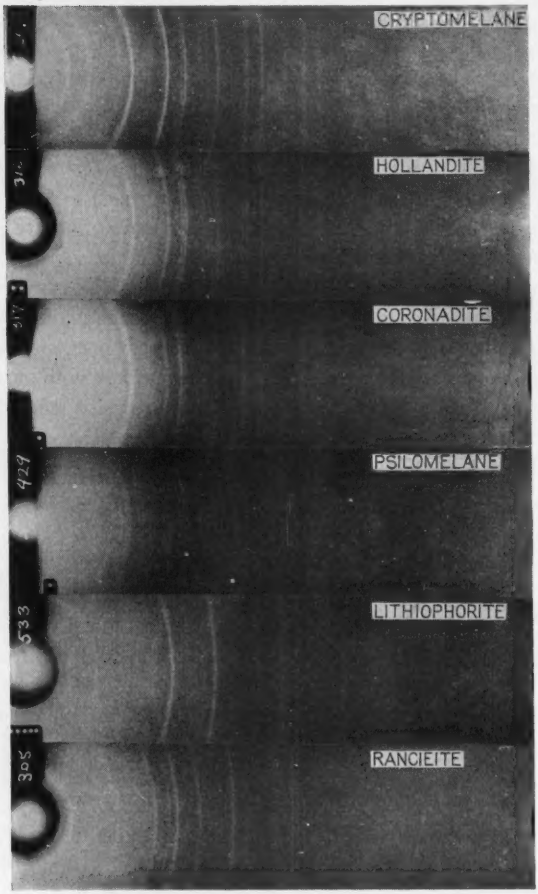



FIG. 2. X-ray powder photographs of some manganese minerals.

(2) Massive, friable, with grain size usually somewhat larger than the compact variety. Easily broken down with the fingers.

(3) Botryoidal, occurring in radiating crystals or crystallized masses with an external form resembling clusters of grapes, which may be large or small. There may be several composite bands

making up each "grape." In many of the finely banded specimens composed of harder and softer bands, the softer portion is pyrolusite, and the harder portion may be pyrolusite, cryptomelane, or psilomelane.

(4) Crystals, commonly as pseudomorphs after manganite; in long prismatic crystals which may have several terminal forms, or may have only the base, or may taper to a sharp wedge. Good tetragonal crystals with well-developed terminal forms are known only from Platten, Bohemia ("polianite").

*Ramsdellite* [12]—$MnO_2$. Orthorhombic. Color iron-gray to black. Streak black. Hardness 3. Sp. gr. 4.7. Occurs as thick tabular crystals and as massive material that has a platy appearance, owing to two cleavages at right angles. Commonly mixed with pyrolusite (transformation product ?). Inverts to pyrolusite when heated at 300°.

*Ranciéite*—$(Ca, Mn^{II})Mn_4{}^{IV}O_9 \cdot 3H_2O$(?). Color silver-gray, brown, brownish-black. Streak purplish-brown. Very soft. Sp. gr. 3.3, but the apparent specific gravity is very low. Occurs as silver-gray incrustations and thin flakes, as brown, compact masses which would probably be termed "wad" in the field, also as brownish-black friable masses.

Ranciéite is usually listed as a variety of psilomelane. Our X-ray and chemical study shows it to be an independent species.

*Accessory Elements.*—Cobalt is commonly present in cryptomelane, psilomelane, and hollandite, with CoO ranging from 0 to 2.5 per cent. Cobalt is present in appreciable percentage in all samples of lithiophorite examined. Nickel has been found in appreciable percentage only in lithiophorite. Zinc is commonly present only in very small percentages, but up to 8 per cent ZnO has been found in samples of cryptomelane, and up to 1.5 per cent ZnO in coronadite. Tungsten is present in some psilomelane samples, most commonly less than 1 per cent $WO_3$, but psilo-

[12] This is the first use of this name in print. The mineral was described in 1932 by Ramsdell (op. cit., p. 148) as a possible dimorph of pyrolusite. Examination of new material and of Ramsdell's specimen has established the validity of this mineral species. A more detailed description is in preparation.

melane from Sodaville, Nevada, contained 4.88 per cent $WO_3$.[13] Tungsten is not present in most samples of cryptomelane, but Gonyer reported 2.24 per cent $WO_3$ in a sample from Golconda, Nevada.[14] Small percentages of copper, arsenic, strontium and vanadium have been found in some specimens.

## IDENTIFICATION.

It is evident that identifications based on physical properties are highly uncertain, owing to the variability of these properties and their overlapping. Hardness is a particularly poor criterion. The streak may be helpful, but must be used with caution. A detailed discussion of the optical properties of the minerals is reserved for later publication; however, it may be said that identification of well-crystallized material is possible, but that identification of fine-grained material is as yet uncertain.

Qualitative tests for lead, barium, potassium, lithium, calcium and aluminum may be helpful. A flame test, made by introducing the powdered mineral directly into the flame on a platinum or nichrome wire, may give useful information. A strong potassium flame (use of a blue glass or Merwin screen may be necessary) is a fairly good indication of cryptomelane; a crimson flame of lithiophorite. The barium manganates give little or no barium flame when tested in this way. If the powdered mineral on the wire is moistened with hydrochloric acid and held in the flame, a strong green flame (caused by manganese chloride) is observed which disappears in a few seconds and is followed by the persistent barium flame.

X-ray powder pictures are the only certain means of identifying many samples. Qualitative chemical tests must also be made to identify cryptomelane, hollandite, or coronadite, whose X-ray powder photographs differ only slightly. In order that others

[13] Analyzed by F. A. Gonyer and described by Kerr, P. F.: Tungsten-bearing manganese deposit at Golconda, Nevada. G. S. A., Bull. 51: 1359–1390, 1940. This is his No. 4, Table 3, p. 1382.

[14] Described by Kerr, op. cit., p. 1382, Table 3, No. 1. We are indebted to Dr. Kerr for furnishing these samples for X-ray study.

TABLE 1.

$D$ = spacings in Angstrom units; $I$ = estimated intensities.
All photographs were made with Fe radiation.

*Bixbyite*, Thomas Range, Utah.

| $D$ | $I$ | $D$ | $I$ | $D$ | $I$ |
|---|---|---|---|---|---|
| 4.671 | 1 | 1.716 | 2.5 | 1.255 | 2 |
| 4.204 | 1 | 1.654 | 9 | 1.194 | 2 |
| 3.824 | 6 | 1.614 | 2 | 1.175 | 4 |
| 3.346 | 1 | 1.564 | 2 | 1.155 | 4 |
| 2.985 | 3 | 1.527 | 3 | 1.139 | 3 |
| 2.716 | 10 | 1.480 | 2 | 1.123 | 3 |
| 2.506 | 2 | 1.451 | 3 | 1.105 | 3 |
| 2.350 | 4 | 1.418 | 8 | 1.091 | 3 |
| 2.206 | 2 | 1.385 | 4 | 1.077 | 7 |
| 2.104 | 1 | 1.356 | 3 | 1.075 | 4 |
| 2.004 | 4 | 1.327 | 1 | 1.050 | 6 |
| 1.920 | 1 | 1.304 | 2 | 1.048 | 2 |
| 1.869 | 4 | 1.279 | 3 | 1.037 | 1 |

*Braunite.*

| $D$ | $I$ | $D$ | $I$ | $D$ | $I$ |
|---|---|---|---|---|---|
| 4.66 | 1 | 1.83 | 1 | 1.22 | 1 |
| 4.21 | 1 | 1.80 | 1 | 1.18 | 2 |
| 3.48 | 3 | 1.73 | 3 | 1.17 | 3 |
| 3.32 | 1 | 1.65 | 9 | 1.15 | 1 |
| 2.96 | 2 | 1.525 | 3 | 1.10 | 1 |
| 2.72 | 6 | 1.49 | 2 | 1.08 | 2 |
| 2.68 | 10 | 1.46 | 2 | 1.075 | 7 |
| 2.48 | 1 | 1.42 | 8 | 1.07 | 2 |
| 2.33 | 5 | 1.41 | 6 | 1.051 | 5 |
| 2.14 | 6 | 1.37 | 1 | 1.05 | 2 |
| 1.86 | 2 | 1.355 | 4 | 1.049 | 1 |

*Coronadite*, Coronado vein, Graham Co., Arizona (type material).

| $D$ | $I$ | $D$ | $I$ | $D$ | $I$ |
|---|---|---|---|---|---|
| 3.487 | 9 | 1.83 | 7 | 1.37 | 3 |
| 3.327 | 1 | 1.74 | 2 | 1.36 | 6 |
| 3.113 | 10 | 1.68 | 3 | 1.30 | 2 |
| 2.387 | 7 | 1.63 | 7 | 1.24 | 3 |
| 2.198 | 8 | 1.53 | 8 | 1.22 | 3 |
| 2.159 | 6 | 1.42 | 1 | 1.20 | 2 |
| 1.940 | 3 | 1.39 | 3 | 1.18 | 4 |

*Cryptomelane*, Mowry Mine, Patagonia dist., Arizona.

| $D$ | $I$ | $D$ | $I$ | $D$ | $I$ |
|---|---|---|---|---|---|
| 6.863 | 9 | 2.097 | 1 | 1.385 | 0.5 |
| 4.892 | 8 | 1.961 | 1 | 1.347 | 5 |
| 3.445 | 3 | 1.917 | 2 | 1.289 | 1 |
| 3.105 | 10 | 1.820 | 5 | 1.230 | 0.5 |
| 2.445 | 3 | 1.633 | 4 | 1.209 | 0.5 |
| 2.387 | 7 | 1.618 | 4 | 1.190 | 0.5 |
| 2.305 | 1 | 1.544 | 1 | 1.135 | 0.5 |
| 2.183 | 4 | 1.528 | 6 | 1.073 | 1 |
| 2.145 | 5 | 1.423 | 2 | 1.052 | 1 |

TABLE 1—(*Continued*).

*Hausmannite*, Långban, Sweden.

| *D* | *I* | *D* | *I* | *D* | *I* |
|---|---|---|---|---|---|
| 4.851 | 7 | 1.626 | 1.5 | 1.224 | 3 |
| 3.048 | 5 | 1.568 | 6 | 1.213 | 1 |
| 2.869 | 2 | 1.534 | 8 | 1.187 | 3 |
| 2.736 | 9 | 1.459 | 1 | 1.173 | 3 |
| 2.465 | 10 | 1.431 | 5 | 1.140 | 1 |
| 2.331 | 5 | 1.402 | 1 | 1.126 | 4 |
| 2.020 | 6 | 1.375 | 1 | 1.093 | 1 |
| 1.809 | 1 | 1.337 | 2 | 1.073 | 5 |
| 1.775 | 5 | 1.320 | 3 | 1.051 | 3 |
| 1.686 | 2 | 1.236 | 1 | | |

*Manganite*, Ihlfeld, Harz.

| *D* | *I* | *D* | *I* | *D* | *I* |
|---|---|---|---|---|---|
| 3.700 | 1 | 1.694 | 5 | 1.208 | 1 |
| 3.385 | 10 | 1.661 | 9 | 1.179 | 4 |
| 3.096 | 1 | 1.629 | 5 | 1.152 | 4 |
| 2.883 | 1 | 1.493 | 5 | 1.130 | 8 |
| 2.616 | 9 | 1.428 | 1 | 1.109 | 4 |
| 2.506 | 2 | 1.424 | 4 | 1.094 | 3 |
| 2.406 | 6 | 1.414 | 1 | 1.076 | 3 |
| 2.359 | 0.5 | 1.316 | 4 | 1.052 | 1 |
| 2.310 | 0.5 | 1.287 | 2 | 1.024 | 8 |
| 2.263 | 7 | 1.275 | 1 | 1.022 | 2 |
| 2.186 | 3 | 1.257 | 1 | | |
| 1.771 | 6 | 1.239 | 2 | | |

*Psilomelane*, Schneeberg, Saxony.

| *D* | *I* | *D* | *I* | *D* | *I* |
|---|---|---|---|---|---|
| 4.205 | 1 | 2.663 | 1 | 1.734 | 2 |
| 3.825 | 1 | 2.402 | 8 | 1.712 | 2 |
| 3.488 | 8 | 2.364 | 1 | 1.636 | 2 |
| 3.318 | 2 | 2.251 | 3 | 1.562 | 4 |
| 3.217 | 1 | 2.191 | 10 | 1.524 | 1 |
| 2.972 | 1 | 2.138 | 2 | 1.424 | 4 |
| 2.842 | 4 | 1.816 | 5 | 1.403 | 6 |

*Hollandite*, Kajlidongri, Jhabua State, India.

| *D* | *I* | *D* | *I* | *D* | *I* |
|---|---|---|---|---|---|
| 4.95 | 1 | 1.82 | 3 | 1.35 | 6 |
| 3.48 | 7 | 1.75 | 1 | 1.31 | 1 |
| 3.10 | 10 | 1.69 | 1 | 1.30 | 1 |
| 2.38 | 4 | 1.64 | 5 | 1.29 | 2 |
| 2.19 | 5 | 1.62 | 5 | 1.17 | 2 |
| 2.14 | 4 | 1.53 | 8 | 1.16 | 2 |
| 1.95 | 1 | 1.43 | 1 | 1.15 | 2 |
| 1.93 | 1 | 1.42 | 1 | 1.09 | 6 |
| 1.91 | 1 | 1.395 | 1 | 1.08 | 6 |
| 1.83 | 3 | 1.36 | 6 | | |

TABLE 1—(*Continued*).

*Lithiophorite*, White Oak Mt., Bradley Co., Tenn.

| *D* | *I* | *D* | *I* | *D* | *I* |
|---|---|---|---|---|---|
| 9.407 | 9 | 2.27 | 1 | 1.38 | 5 |
| 5.13 | 1 | 2.12 | 1 | 1.23 | 6 |
| 4.70 | 10 | 2.04 | 1 | 1.18 | 2 |
| 3.13 | 3 | 1.87 | 8 | 1.14 | 2 |
| 2.48 | 1 | 1.55 | 6 | | |
| 2.35 | 9 | 1.44 | 7 | | |

*Pyrolusite*, Platten, Bohemia.

| *D* | *I* | *D* | *I* | *D* | *I* |
|---|---|---|---|---|---|
| 4.08 | 2 | 2.190 | 3 | 1.434 | 2 |
| 3.425 | 2 | 2.108 | 4 | 1.387 | 3 |
| 3.346 | 1 | 1.964 | 4 | 1.356 | 5 |
| 3.096 | 10 | 1.785 | 1 | 1.158 | 1 |
| 2.651 | 0.5 | 1.708 | 1 | 1.120 | 2 |
| 2.537 | 1 | 1.618 | 8 | 1.098 | 2 |
| 2.396 | 6 | 1.550 | 7 | 1.053 | 3 |

*Ramsdellite*, Lake Valley, New Mexico.

| *D* | *I* | *D* | *I* | *D* | *I* |
|---|---|---|---|---|---|
| 4.08 | 10 | 1.95 | 1 | 1.35 | 5 |
| 3.20 | 1 | 1.88 | 5 | 1.31 | 2 |
| 3.10 | 9 | 1.82 | 2 | 1.30 | 3 |
| 2.53 | 8 | 1.64 | 6 | 1.27 | 1 |
| 2.40 | 4 | 1.60 | 7 | 1.25 | 1 |
| 2.32 | 4 | 1.53 | 3 | 1.16 | 1 |
| 2.13 | 5 | 1.52 | 2 | 1.12 | 1 |
| 2.09 | 3 | 1.46 | 5 | 1.07 | 3 |
| 2.04 | 2 | 1.42 | 3 | 1.05 | 3 |

*Ranciéite*, Oriente Province, Cuba.

| *D* | *I* | *D* | *I* | *D* | *I* |
|---|---|---|---|---|---|
| 7.508 | 10 | 2.053 | 4 | 1.349 | 1 |
| 3.786 | 1 | 1.988 | 2 | 1.322 | 1 |
| 3.737 | 8 | 1.840 | 2 | 1.277 | 0.5 |
| 3.113 | 0.5 | 1.747 | 5 | 1.247 | 0.5 |
| 2.956 | 0.5 | 1.649 | 5.5 | 1.229 | 0.3 |
| 2.698 | 9 | 1.486 | 2.5 | 1.211 | 0.5 |
| 2.454 | 3 | 1.443 | 1 | 1.165 | 0.5 |
| 2.331 | 7 | 1.416 | 6 | 1.101 | 0.7 |
| 2.137 | 1 | 1.390 | 3 | 1.072 | 0.5 |

may identify these minerals, spacings and estimated intensities are given in Table 1 for the commoner minerals and for those for which new data are presented in this paper. The data in Table 1 were obtained by Dr. Clifford Frondel of Harvard University. Our own measurements agree well with these values, but are less precise. We are grateful to Dr. Frondel for his kindness in allowing us to publish his values.

## LIST OF MANGANESE OXIDE MINERALS STUDIED IN THE GEOLOGICAL SURVEY LABORATORY.

*Bixbyite*
- New Mexico, Catron Co.
- India, Sitapur ("sitaparite").

*Braunite*
- Arizona, Cochise Co., Bisbee.
- California.
  - Humboldt Co., Ft. Seward Mine.
  - Plumas Co.
  - Stanislaus Co., Buckeye Mine.
- Maine, Aroostook Co.
- Missouri, Shannon Co., Seaman No. 1 prospect.
- Nevada, Humboldt Co., Golconda.
- Texas, Mason Co., Spiller Mine.
- Colombia, Antioquia, Las Mercedes Mine.
- Costa Rica, Chanchoz.
- Cuba, Oriente Province.

*Cesarolite*
- Algeria.

*Coronadite*
- Arizona, Pinal Co., Superior Mining dist., Magma Mine.
- California, Inyo Co., Modoc Mining dist.
- Morocco, Bou Tazoult.

*Cryptomelane*
- Alabama, Clay Co.
- Arizona, Cochise Co., Tombstone, Oregon-Prompter Mine.
- Arkansas, Polk Co., Sugar Stick prospect near Mena.
- Missouri, Shannon Co., Seaman No. 1 prospect.
- Montana
  - Granite Co., Philipsburg.
  - Madison Co., Cherry Creek.
- Nevada, White Pine Co., Ely.
- New Jersey, Sussex Co., Franklin.
- New Mexico
  - Luna Co., Deming.
  - Sierra Co., Lake Valley.
- Pennsylvania, Bedford Co., Shannon Valley.
- Tennessee
  - Mountain City dist., Belle Hawkins tract.
  - Stony Creek Valley.
- Virginia
  - Augusta Co.
    - Lyndhurst Mine near Sherando.
    - Robinson Hollow.
    - Stuarts Draft, Mt. Torrey Mine.
  - Bland Co., Virginia Hardwood Lumber Co. Mine.
  - Campbell Co.
    - Flat Creek, Bell Mine.
    - Lawyers.
    - Mortimer Mine.

Piedmont Mine.
Page Co., Stanley Mine.
Rockbridge Co., Mine Bank Mine.
Brazil, Mato Grosso, Urucum.
Cuba, Oriente Province.
France, Romanèche.
India, Sitapur.
Garbham, Madras.

*Hausmannite*
Arkansas, Independence Co., Batesville, Ozark No. 1, Dave Dunnegan shaft.
Washington, Olympic Peninsula.
Sweden, Långban.

*Hollandite*
Missouri, Reynolds Co., Tucker-Nash prospect.
Montana, Madison Co., Cherry Creek.
New Mexico, Socorro Co., near Socorro.
Tennessee, Shady Valley.
Brazil, Goyaz, San José de Tocantins.
India, Jhabua State, Kajlidongri.
South Africa, Postmasburg.

*Jacobsite*
Washington, Olympic Peninsula.

*Lithiophorite*
Alabama, Cherokee Co.
Tennessee
Bradley Co., White Oak Mt.
Hickman Co., Coble.
Dominican Republic, Loma Caribe.
Silesia, Rengersdorf.

*Manganite*
Michigan, Marquette Co., Negaunee, Lucy Mine.
Utah, Emery Co., Green River.
Cuba, Oriente Provine.
Germany, Ihlfeld.

*Manganosite*
New Jersey, Sussex Co., Franklin.

*Psilomelane*
Alabama, Cherokee Co.
Arizona, Yavapai Co., Castle Creek.
Graham Co.
California, Paymaster dist., Tolbard Mine.
New Mexico
Dona Anna Co., Rincon, Morgan Mine.
Luna Co., Deming.
Nevada, Mineral Co., Sodaville.
Tennessee, Shady Valley.
Texas, Jeff Davis Co., Chispa, Mayfield prospect.
Utah, Daggett Co., Manila.
Virginia
Appomattox Co., Hancock-Ferguson Mine.
Campbell Co., Lynchburg, Pribble Mine.

Frederick Co., Mineral Ridge Mine.
Page Co.
Compton, Compton Mine.
Stanley Mine.
Vesuvius Co., Hogpen Hollow prospect.
Wythe Co.
Cuba, Oriente Province.
France, Romanèche.
Germany, Schneeberg.

*Pyrochroite*
Jugoslavia, Ljubija.

*Pyrolusite*
Georgia, Cartersville district.
Montana, Granite Co., Phillipsburg.
Nevada
Humboldt Co., Golconda.
White Pine Co., Ely.
New Mexico
Grant Co., Silver City, Boston Hill Mine.
Sierra Co., Lake Valley.
Tennessee
Mountain City dist., Belle Hawkins tract.
Washington Co., Embreeville.
Utah
Drum Mts.
Emery Co., Green River.
Virginia
Appomattox Co., Stonewall Mine.
Augusta Co.
Black Shaft.
Crimora.
Stuarts Draft, Mt. Torrey Mines.
Campbell Co., Piedmont Mine.
Frederick Co., Mineral Ridge Mine.
Rockbridge Co.
Hogpen Hollow prospect.
Mine Bank Mine.
Vesuvius Mine.
Tazewell Co., Bluefield, Suiter Mine.
Wyoming
Albany Co.
J. B. C. Mine.
Mule Creek.
Africa, Gold Coast.
Bohemia, Platten.
Brazil, Morro da Mina.
Costa Rica, Pavones.
Cuba, Oriente Province.
Nova Scotia, Pictou Co., East River.
Russia, Caucasus.

*Quenselite*
Sweden, Långban.

*Ramsdellite*
New Mexico, Sierra Co., Lake Valley.
Nova Scotia, Pictou Co., East River.
Turkey, Roumelia, Moustapha Pasha, Kodjas Karil Mine.
*Ranciéite*
Arkansas, Independence Co., Batesville.
North Dakota, Rolette Co., Dunseith.
Cuba, Oriente Province.

## APPLICATIONS.

It is hoped that the data here presented will make possible a new approach to some technical problems involving the manganese oxide minerals. For example, X-ray study may throw light on the reasons, at present unknown, why some ore makes good dry cells, whereas other ores of higher $MnO_2$ content do not.[15] Likewise, identification of the manganese mineral or minerals present in an ore may be helpful in working out methods of beneficiation not purely empirical.

## ACKNOWLEDGMENTS.

We are indebted to Clifford Frondel of Harvard University for the use of his data; to L. S. Ramsdell of the University of Michigan and P. F. Kerr of Columbia University for the loan of specimens studied by them; to W. F. Foshag and E. P. Henderson of the U. S. National Museum for loaning us many specimens.

This project was formulated in discussions with D. F. Hewett, C. F. Park, Jr., T. A. Hendricks and Charles Milton of the Geological Survey, to whom we are also indebted for much helpful advice. We have also had the benefit of optical work by Milton, X-ray work by J. M. Axelrod, and advice and criticism by W. T. Schaller and C. S. Ross. Many of the specimens studied were collected by geologists of the Geological Survey, too numerous to list here.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.
*January 25, 1943.*

[15] Chambers, G. H.: Industrial Minerals and Rocks. 1937. P. 450.

# LAYERED OR BANDED CHROMITE AT CAMPO FORMOSO, BAÍA, BRAZIL.[1]

W. D. JOHNSTON, JR., AND H. CAPPER A. DE SOUZA.

ABSTRACT.

Chromite at Campo Formoso occurs in layers a few millimeters to a meter or more in thickness alternating with layers of serpentine derived from olivine. Where not disturbed by faulting, individual layers of both chromite and serpentine are remarkably persistant both in thickness and extent. The resemblance to a sedimentary rock is so strong that the suggestion is made that these layered rocks were formed by the settling of alternate showers of chromite and olivine crystals on the floor of a magma chamber.

## INTRODUCTION.

The three known chromite localities in the State of Baía [2] Brazil, are Santa Luzia, Campo Formoso, and Saude. These have been described in detail in the recent report by de Souza.[3] Other chromite localities in Brazil are Piüi in the State of Minas Gerais [4] and an undescribed deposit near Pouso Alto in the State of Goiaz. This paper is concerned only with the origin of the Campo Formoso deposits.

[1] Published with the permission of the Chief, Metals and Minerals Division, Board of Economic Warfare, and the Director, Departamento Nacional da Produção, Mineral.

[2] Williams, H. E.: Chromite deposits of Bahia, Brazil. Eng. and Min. Jour., Vol. 3, February 1921. Rego, Luiz Flores de Moraes: Chromita do Brasil. Serviço Geol. e Mineral., Vol. 56, 1931. Freise, F. W.: Brasilianische Chromerze. Met. u. Erz, 29: 456–8, 1932. Leonardos, O. H.: Ocorrencia de garnierita associada á chromita. Serviço de Fomento da Produção Mineral, 9: 57–61, 1935. Oliveira, A. I.: Deposito de Chromita do Estado da Baía. Serviço de Fomento da Produção Mineral, Avulso 12, 1936. de Mello, J. L., Jr.: Mina de Chromo de Cascabulhos. Mineração e Metallurgia, 2: 108–110, 1937. Montes Flores, M. Macambyra: Geologia do Estado da Bahia. Revista do Instituto Geographico e Historico da Bahia, No. 63, 1937. Wright, C. W.: Mineral resources, production and trade of Brazil. Foreign Min. Quart., 4, No. 1: 34–36, 1941.

[3] de Souza, H. C. A.: Cromo na Baía. Divisão de Fomento da Produção Mineral, Bol. 54, 1942.

[4] Barbosa, Octavio, and Lacourt, F.: Chromita em Piüi, Minas Gerais. Mineração e Metalurgica, 5: 39–43, 1940.

GENERAL GEOLOGICAL RELATIONS.

A narrow strip of serpentine and talc schist lies at the foot of a northwestward facing quartzite escarpment (Fig. 1). The strip of basic rocks is about 8 kilometers long and, in most places, less than one kilometer in width. On the north and northwest side of the basic strip are granites and granite gneiss. Neither

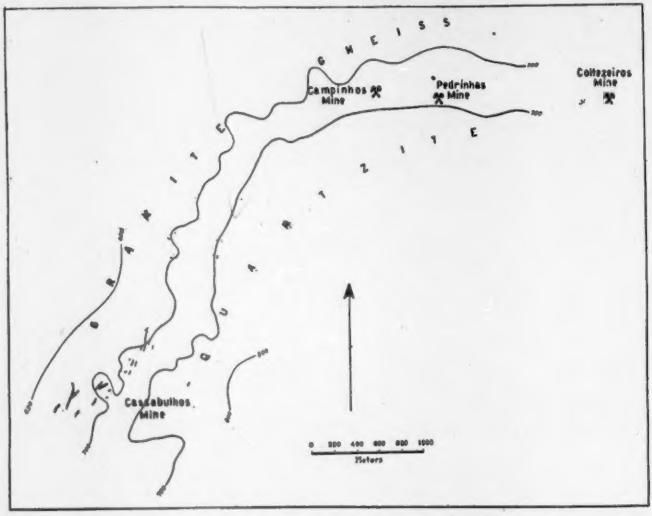



FIG. 1. Sketch map showing the positions of the various mines and the outcrop pattern of the thicker, vertical or steeply dipping chromite layers at the Cascabulhos Mine.

the quartzite-serpentine or the serpentine-granite contacts are well enough exposed to definitely determine their nature but it appears most probable that both contacts are faults.

The talc schist, which has no chromite, occupies more than half of the outcrop area of basic rocks. The serpentine area, on the northwestern edge of the strip of basic rocks, contains the chromite. De Souza's [5] recent report includes geological maps of the area.

[5] de Souza, H. A.: op. cit., Figs. 6–10.

The chromite occurs in layers a few millimeters to a meter or more in thickness alternating with layers of serpentine derived from olivine. These chromite layers appear to be confined to certain horizons within the serpentine, and geometrically they are truly comparable with bedded or layered rocks.

At the Campinhos Mine, horizontal layers of chromite and serpentine exposed in open cuts have been faulted in such a way

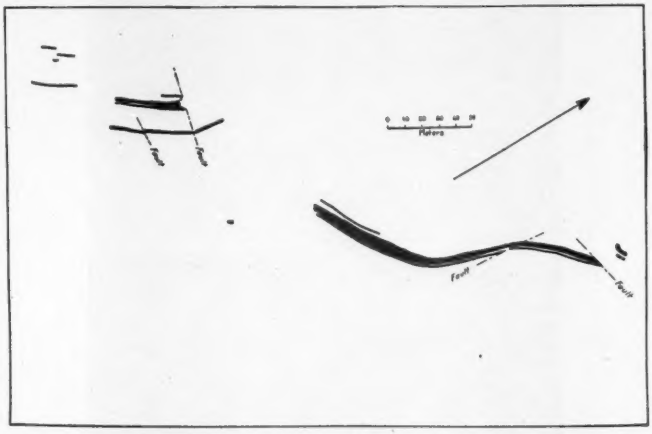



FIG. 2. Sketch map of the No. 16 orebody, Cascabulhos Mine showing the outcrop pattern of the steeply dipping thicker chromite layers that are being mined.

that a vertical section of at least 20 meters is exposed. Ninety-three horizontal layers of chromite, each separated by a layer of serpentine were counted in a vertical section of one meter. Other layers of both chromite and serpentine are thicker. Figures 3 to 6 show detailed section in Campinhos Mine. The thickness of the chromite and serpentine layers shown in Figs. 5 and 6 are fairly accurated as these illustrations were traced from Kodachrome slides projected on drawing paper.

At Cascabulhos Mine (Fig. 2) chromite layers 1 to 3 meters thick stand vertically or are steeply dipping. However, the presence of finely laminated chromite with the same dip and strike as

the thicker layers relates the Cascabulhos mine with Campinhos and indicates a common origin for the chromite in both mines. Pedrinhas and Coitezeiros Mines are characterized generally by thinner chromite layers.

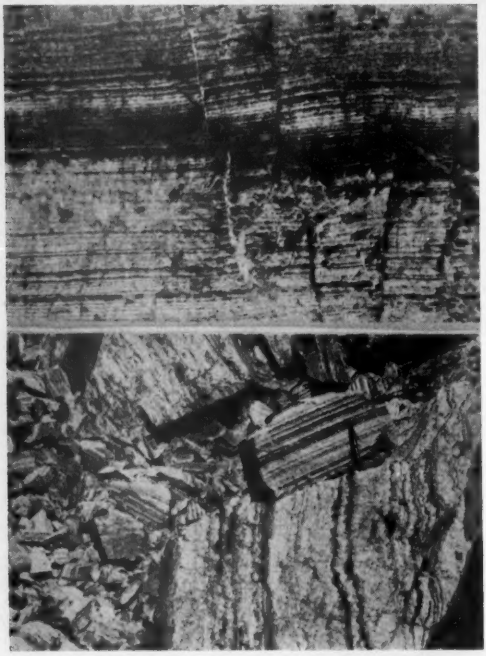


FIG. 3 (Top). Layered chromite and serpentine after olivine, Campinhos Mine, 1942. The section shown is about one meter thick.

FIG. 4 (Bottom). Talus blocks of layered chromite, Campinhos Mine, 1942. The fountain pen used for a scale is 12 cm. long.

The chrome-bearing rocks are cut by many faults. In the open cuts at Campinhos and Pedrinhas mines, small faults offset the layering by a few centimeters (Fig. 3). At Campinhos, a larger vertical fault striking through the pit has a throw of at least 10 meters, for the stratigraphic succession of thick and thin beds on

opposite sides of the fault do not match. Two of the larger faults at Campinhos are shown in Fig 6. At Cascabulhos mine, the No. 16 orebody (Fig. 2) is offset to the right in two places but the actual faults are concealed by surficial material.

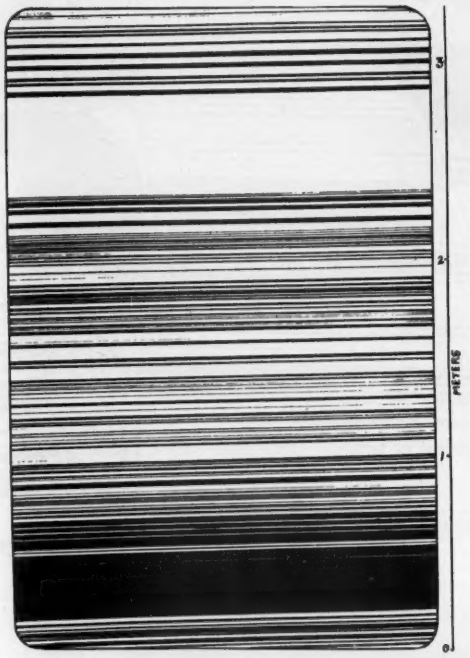



FIG. 5. Tracing of a photograph of a wall at the Campinhos Mine. Black is chromite and white is serpentine after olivine.

The chromite layers, in thin section, show chromite octahedra, each separated from its neighbor by a sheath of antigorite. Some layers are mostly chromite with little serpentine, and, in these, the chromite crystals touch. Other layers are mostly serpentine with relics of olivine and contain scattered chromite crystals. All gradations between these extremes exist. A few sections show relics of large olivine crystals surrounded by swarms of chrome

crystals. In general, the microscopic evidence seems to indicate essentially contemporaneous crystallization of chromite and olivine.

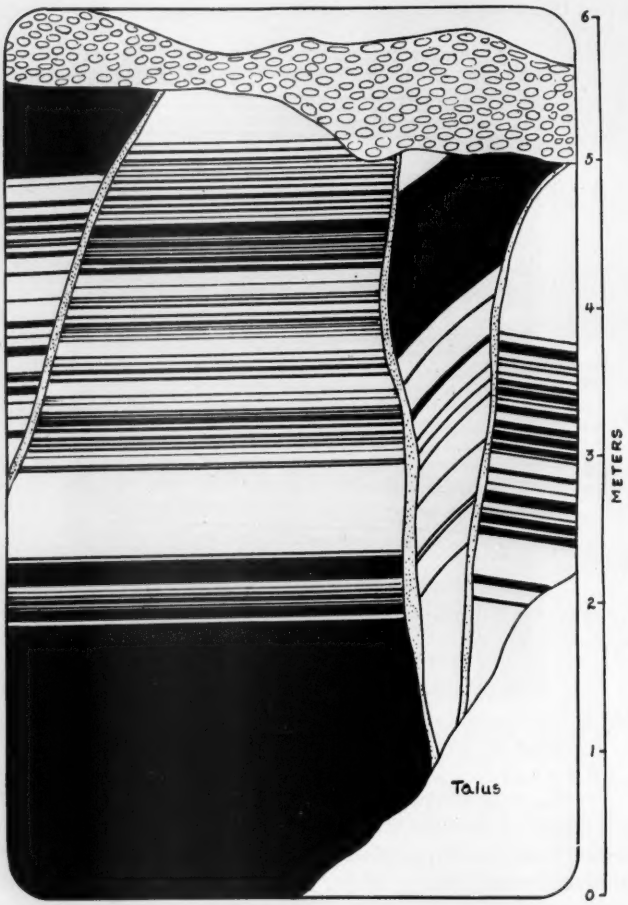



FIG. 6. Tracing of a photograph of a wall at the Campinhos Mine. Black is chromite and white is serpentine after olivine.

The same variation in the spacing of chromite crystals in serpentine that is seen in thin section appears also on a larger scale in some of the thicker chromite layers that are mined for lump ore. Figure 7 is a diagrammatic sketch of a layer at the Cascabul-

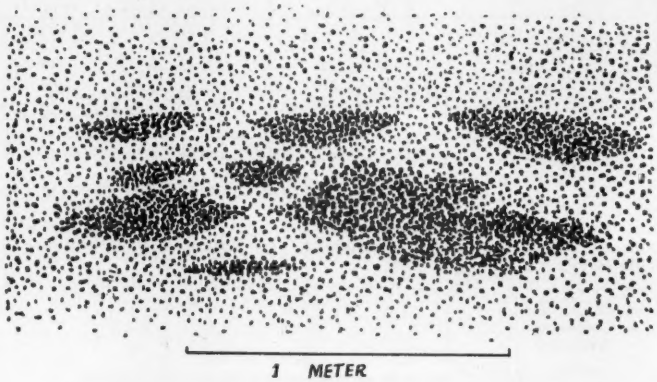



FIG. 7. Diagram to illustrate the variation in a distribution of chromite crystals within a chromite layer. Interstitial material is serpentine after olivine. Number 16 orebody, Cascabulhos Mine.

hos mine wherein dense packing of chromite crystals grades into loose packing. In places, the densely packed masses are of meter size; elsewhere they are measured in centimeters. This lack of homogeneity in some of the thicker layers necessitates the careful inspection of each piece of ore going into a high grade shipment.

## COMPOSITION OF THE CHROMITE.

The following three complete analyses of chromite concentrates from the Campo Formoso area were made by Mr. R. E. Stevens, of the U. S. Geological Survey, on samples collected by Johnston in 1941. The samples were separated by heavy liquids and, as is indicated by the low silica, are fairly free from serpentine or other silicates.

ANALYSES OF CHROMITE CONCENTRATES.
*(R. E. Stevens, Analyst.)*

| | *a.* | *b.* | *c.* |
|---|---|---|---|
| $Cr_2O_3$ | 56.24 | 58.18 | 58.60 |
| $Al_2O_3$ | 12.42 | 11.30 | 11.08 |
| $Fe_2O_3$ | 4.44 | 3.46 | 3.94 |
| FeO | 12.72 | 13.28 | 12.06 |
| MgO | 12.47 | 12.89 | 13.57 |
| MnO | .37 | .25 | .15 |
| $TiO_2$ | .21 | .15 | .19 |
| CaO | .12 | .06 | .04 |
| $SiO_2$ | .38 | .22 | .22 |
| $H_2O$ | .44 | .26 | .26 |
| Total | 99.81 | 100.05 | 100.11 |
| Cr | 38.50 | 39.80 | 40.10 |
| Fe | 13.00 | 12.74 | 12.13 |
| Ratio Cr/Fe | 2.98 | 3.12 | 3.31 |
| Impurity | Serpentine | Serpentine | Serpentine |
| Ratio $RO/R_2O_3$ | .93 | .97 | .95 |

*a.* Cascabulhos.
*b.* Campinhos.
*c.* Pedrinhas.

PARTIAL ANALYSES OF CHROMITE CONCENTRATES.
*(R. E. Stevens, Analyst.)*

| | *d.* | *e.* | *f.* |
|---|---|---|---|
| Cr | 38.39 | 38.70 | 38.46 |
| Fe | 14.69 | 15.23 | 12.51 |
| Ratio Cr/Fe | 2.61 | 2.54 | 3.07 |

*d.* Cascabulhos.
*e.* Campinhos.
*f.* Coitereiros.

Other samples of concentrates from the Pedrinhas mine analyzed in the Departamento Nacional da Produção Mineral gave a content of $Cr_2O_3$ ranging from 35.20 to 54.50 per cent and a Cr/Fe ratio of 1.51 to 2.60.

It thus appears that there is considerable range in the composition of the banded ore. Unfortunately no systematic analyses of concentrates, layer by layer, were made.

Figure 8 is an attempt to show diagrammatically the composition of chromite, which might be written $(Fe,Mg)O.(Fe, Al, Cr)_2O_3$, in relation to the end members of the series. The RO

members, FeO and MnO, are represented by the top and bottom of the prism, while the edges of the prism represent the $R_2O_3$ members, $Al_2O_3$, $Fe_2O_3$, and $Cr_2O_3$.

From the few geologically fragmental analyses at hand, it appears likely that there may be some stratigraphically systematic

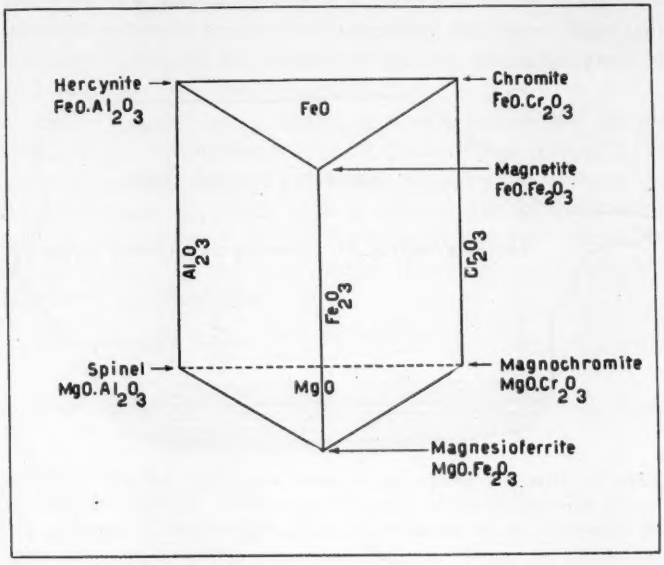



FIG. 8. Diagram showing the end members of (Fe, Mg)O·(Fe, Al, $Cr)_2O_3$.

variation in the composition of the chromite such as Sampson and Peoples and Howland [6] appear to have found in the banded chromites of the Stillwater Complex of Montana.

## ORIGIN OF THE DEPOSITS.

The remarkable persistence of individual layers and the constancy in detail of the stratigraphic succession of thin and thick layers give these rocks the geometry of sediments.

[6] Oral communication to Johnston.

In the field, the authors searched for chromite that cut serpentine layers or serpentine that cut chromite layers, such as would be found if the deposits were formed by one mineral injecting the other. Lacking all evidence for such cross cutting, the hypothesis of an injection gneiss was abandoned.

Search was also made for a pattern of overlapping flat lenses that might permit the interpretation that these rocks were formed by recrystallization with the segregation of the component min-

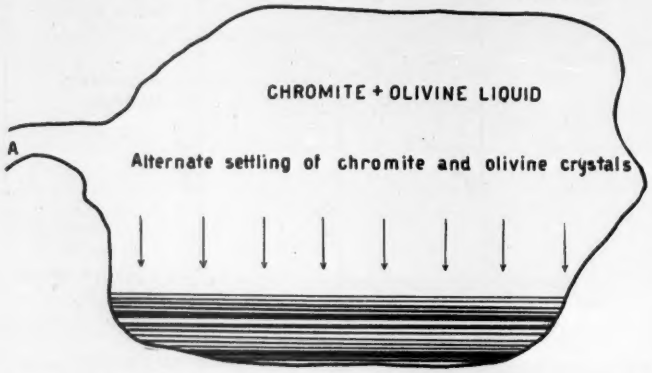



FIG. 9. Diagram illustrating suggested mechanism for the accumulation of alternate layers of chromite and olivine. Rhythmic changes in the composition of the chromite and olivine liquid might be caused by the addition of new material into the chamber through the channel "A" or by rhythmic changes in pressure or temperature within the chamber itself.

erals. However, the sedimentary geometry of the rocks defeated this explanation.

Previously, Johnston [7] had described banded chromites from California and very vaguely attributed their origin to some kind of flowage. Again, the regularity of the stratigraphic pattern of the Campo Formoso rocks defies such an explanation.

That the sedimentary geometry required a sedimentary origin then appeared to be unescapable. The possibility that these rocks

[7] Johnston, W. D., Jr.: Nodular, orbicular and banded chromite in Northern California, ECON. GEOL., 31: 417–27, 1936.

were water laid was rejected because thin sections of the banded rocks show the same patterns of chromite octahedra separated by serpentine that characterizes most chromite deposits of undoubted igneous origin.

The remaining explanation, that the rocks were formed by some process of sedimentation within a magma chamber seems most probable.

Coats'[8] explanation of primary banding is not adequate to give very thin layers of wide extent.

Figure 9 is a diagram illustrating a suggested method for the accumulation of alternate layers of chromite and olivine. The authors can only suggest that rhythmic changes in the composition of the chromite and olivine liquid might be caused by the addition of new material into the chamber through the channel indicated in the diagram or by rhythmic changes in pressure or temperature within the chamber itself.

RIO DE JANEIRO, BRAZIL,
*November 12, 1942.*

[8] Coats, R. R.: Primary banding in basic plutonic rocks, Jour. Geol., 44: 407–419, 1936.

# STRUCTURAL DETERMINATIONS FROM DIAMOND DRILLING.[1]

JOHN B. MERTIE, JR.

ABSTRACT.

Several problems may arise in the geometrical determinations of strike and dip from core drilling. If the stratigraphic or structural surfaces are plane, as the bedding planes of a homocline, two problems may exist, depending upon whether the drill cores do or do not penetrate to some recognizable horizon. The first of these is solved by a simple graphic interpolation, and is not discussed in this paper. The second, however, is solved for the most general case of three non-parallel drill holes, no one of which is necessarily vertical.

Errors are necessarily present in this solution, due to:

1. Inaccuracies in the measurement of the initial directions and dips of the drill holes.
2. Deviations of the drill holes from their initial directions.
3. Inaccuracies in the measurement of the angles between the axes of the drill cores, and the stratigraphic or structural planes.

The second and third of these causes result in initial errors in the measurement of the core angles. Hence, for this simplest case, error formulæ are developed for finding the final errors in the angles of strike and dip, under certain specified assumptions.

To illustrate the solution, a problem is stated and solved. This problem is of a general nature, selected to show the necessary operations when the three drill holes occur in different octants. The error formulæ are subsequently applied.

For curved surfaces, as where folded beds are present, the same two problems arise, depending upon whether the drill holes do or do not penetrate to some recognizable horizon. Only the first of these problems is considered. It is shown, in this case, that 9 drill holes are required to obtain a satisfactory solution. The method consists essentially in fitting nine known points to a ternary quadric surface; and in determining the equations of the planes tangent to this surface at any of the nine points, or at any other points on the surface. The strikes and dips are then derived from these equations.

[1] Published by permission of the Director, Geological Survey, U. S. Department of the Interior.

## INTRODUCTION.

THE general problem is the determination of the strike and dip of stratigraphic and structural surfaces, utilizing geometrical data obtained from drill holes and drill cores. The directions and dips of the drill holes are known, but the orientations of the cores within the holes are unknown, as it is not possible to remove cores without revolving them. This problem has several aspects, depending upon

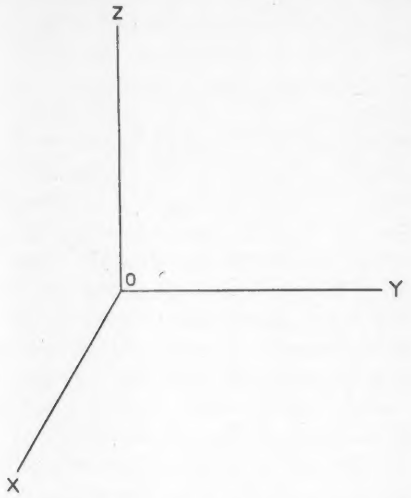



FIG. 1. Right handed system of three-dimensional Cartesian coordinates.

the character of the surfaces, and upon the number and orientation of the drill holes. Obviously, the determination of strike and dip will be least difficult where the surfaces under consideration are essentially plane, as for example the bedding planes of a homocline. Under certain circumstances, however, it is feasible from a larger set of data to obtain satisfactory approximations to the strike and dip of curved surfaces, such as folded bedding planes, but the methods are more involved.

The solutions hereafter shown are based mainly upon elementary applications of solid analytical geometry. Two systems of three-dimensional Cartesian coordinates, known as the right handed and left handed systems, are in common use. In this paper, the right handed system is utilized, as illustrated in Fig. 1. It is also necessary to establish a correspondence between these axes and the points of the compass. The south line is considered to coincide with the positive end of the $X$ axis; the east line coincides with the positive end of the $Y$ axis; and a line from the observer to the zenith coincides with the positive end of the $Z$ axis.

## PLANE SURFACES.

The core from a single vertical drill hole shows the magnitude, but not the direction, of the dip. From two drill holes, one of which is vertical, it is not possible in general to determine the strike, and the direction of the dip; under special conditions, if certain general facts are already known regarding the structure, the data from two such drill holes will yield the desired solution. The conditions under which the proper value can be selected from several answers have been adequately treated by Mead,[2] and trigonometric solutions of this problem were subsequently published by Stein.[3]

From three non-parallel drill holes, none of which is necessarily vertical, a general solution of this problem can always be obtained. If the given data include the lengths of the drill holes, measured to some stratigraphic or structural horizon that can be recognized in all three of the cores, the problem is identical with that of determining strike and dip from three located points on an outcrop; and this, as in plane table mapping, is readily done by a graphic interpolation. If no definite stratigraphic or structural horizon can be recognized in the drill cores, the solution depends primarily upon the observed angles between the axes of the drill cores and certain parallel plane surfaces, such as bedding planes. In this case, both

[2] Mead, W. J.: Determination of attitude of concealed bedded formations by diamond drilling. Econ. Geol., 16: 37–47, 1921.

[3] Stein, H. A.: A trigonometric solution of the two drill-hole problem. Econ. Geol., 36: 84–94, 1941.

the given and the derived data are angular, and neither the initial sites of the drill holes nor their lengths enter into the solution. Hence, without loss of generality, it is possible to move two of the drill holes parallel to themselves, until all three of them appear to have a common starting point, which then is taken as the origin of a system of three-dimensional rectangular coordinates.

The angular magnitudes are as follows:

Let $\theta_1\theta_2\theta_3$ = the angles between the positive direction of the $X$ axis, and the projections of the three drill holes on the $XY$ plane, measured anticlockwise.

$\omega_1\omega_2\omega_3$ = the angles between the axes of the three drill holes and the $XY$ plane; positive when the drill hole is directed upward, and negative when directed downward.

$\alpha_1\alpha_2\alpha_3$ = the angles between the positive direction of the $X$ axis, and the three drill holes.

$\beta_1\beta_2\beta_3$ = the angles between the positive direction of the $Y$ axis, and the three drill holes.

$\gamma_1\gamma_2\gamma_3$ = the angles between the positive direction of the $Z$ axis, and the three drill holes.

$\psi_1\psi_2\psi_3$ = the angles between the axes of the three drill holes, and the stratigraphic or structural planes.

The direction cosines of the axes of the drill holes are readily obtained. Thus, in the spherical right triangle whose sides are $\alpha_0$, $\theta_0$ and $\omega_0$ (with $\pi/2$ opposite $\alpha_0$), we have from Napier's rules,

$$\cos \alpha_0 = \cos \theta_0 \cos \omega_0.$$

Similarly, in the spherical right triangle, whose sides are $\beta_0$, $90° - \theta_0$ and $\omega_0$ (with $\pi/2$ opposite $\beta_0$), we have

$$\cos \beta_0 = \sin \theta_0 \cos \omega_0$$

And finally,

$$\cos \gamma_0 = \cos (90° - \omega_0) = \sin \omega_0.$$

Now consider a normal to the stratigraphic plane, passing through the origin; and designate its direction cosines as $\cos \alpha$, $\cos \beta$, and

$\cos\gamma$. Then the following equations hold:

$$\cos\alpha_1\cos\alpha+\cos\beta_1\cos\beta+\cos\gamma_1\cos\gamma=\cos(90^\circ-\psi_1)=\sin\psi_1$$
$$\cos\alpha_2\cos\alpha+\cos\beta_2\cos\beta+\cos\gamma_2\cos\gamma=\cos(90^\circ-\psi_2)=\sin\psi_2$$
$$\cos\alpha_3\cos\alpha+\cos\beta_3\cos\beta+\cos\gamma_3\cos\gamma=\cos(90^\circ-\psi_3)=\sin\psi_3$$

$$\cos\alpha=\frac{\begin{vmatrix}\sin\psi_1 & \cos\beta_1 & \cos\gamma_1\\ \sin\psi_2 & \cos\beta_2 & \cos\gamma_2\\ \sin\psi_3 & \cos\beta_3 & \cos\gamma_3\end{vmatrix}}{\begin{vmatrix}\cos\alpha_1 & \cos\beta_1 & \cos\gamma_1\\ \cos\alpha_2 & \cos\beta_2 & \cos\gamma_2\\ \cos\alpha_3 & \cos\beta_3 & \cos\gamma_3\end{vmatrix}}=\frac{\begin{vmatrix}\sin\psi_1 & \cos\beta_2 & \cos\gamma_3\end{vmatrix}}{\begin{vmatrix}\cos\alpha_1 & \cos\beta_2 & \cos\gamma_3\end{vmatrix}}$$

$$\cos\beta=\frac{\begin{vmatrix}\cos\alpha_1 & \sin\psi_2 & \cos\gamma_3\end{vmatrix}}{\begin{vmatrix}\cos\alpha_1 & \cos\beta_2 & \cos\gamma_3\end{vmatrix}}$$

$$\cos\gamma=\frac{\begin{vmatrix}\cos\alpha_1 & \cos\beta_2 & \sin\psi_3\end{vmatrix}}{\begin{vmatrix}\cos\alpha_1 & \cos\beta_2 & \cos\gamma_3\end{vmatrix}}.$$

The equation of a stratigraphic plane, that passes through the origin, is

$$x\cos\alpha+y\cos\beta+z\cos\gamma=0.$$

The equation of a trace of this stratigraphic plane in the $XY$ plane, and passing through the origin, is

$$x\cos\alpha+y\cos\beta=0$$

whence

$$\phi=\arctan\left[-\frac{\cos\alpha}{\cos\beta}\right],$$

where $\phi$ is the strike angle measured anticlockwise from the positive end of the $X$ axis, or eastward from the south line.

The dip ($\delta$) of the stratigraphic or structural plane is equal to the direction angle $\gamma$, of the normal to the plane.

Hence

$$\delta=\arccos\frac{\begin{vmatrix}\cos\alpha_1 & \cos\beta_2 & \sin\psi_3\end{vmatrix}}{\begin{vmatrix}\cos\alpha_1 & \cos\beta_2 & \cos\gamma_3\end{vmatrix}}.$$

The direction of the dip is governed by the signs of the coefficients of $x$, $y$ and $z$, as follows:

| $\cos \alpha$ | + | + | + | + | − | − | − | − |
|---|---|---|---|---|---|---|---|---|
| $\cos \beta$ | + | + | − | − | + | + | − | − |
| $\cos \gamma$ | + | − | + | − | + | − | + | − |
| $\delta$ | S.E. | N.W. | S.W. | N.E. | N.E. | S.W. | N.W. | S.E. |

If the direction cosines of $\alpha$ or $\beta$ vanish, the following relationships hold:

| $\cos \alpha$ | 0 | 0 | 0 | 0 | + | + | − | − |
|---|---|---|---|---|---|---|---|---|
| $\cos \beta$ | + | + | − | − | 0 | 0 | 0 | 0 |
| $\cos \gamma$ | + | − | + | − | + | − | + | − |
| $\delta$ | E. | W. | W. | E. | S. | N. | N. | S. |

If $\cos \gamma = 0$, $\delta = 90°$
$\cos \alpha = 1$, strike is E–W, dip 90°
$\cos \beta = 1$, strike is N–S, dip 90°
$\cos \gamma = 1$, $\delta = 0°$.

## ERRORS.

Errors in the application of this method may result from various causes, of which the following are important:

1. Inaccuracies in the measurement of the initial directions and dips of the drill holes.
2. Deviations of the drill holes from their initial directions.
3. Inaccuracies in the measurement of the angles between the axes of the drill cores and the stratigraphic or structural planes.

The first of these is doubtless the least important. If the drill holes are long, the greatest error will result from the second cause; but if they are short, the second and third causes may be about equally important, and both will be reflected in the values of $\psi_1$, $\psi_2$ and $\psi_3$. It has therefore seemed desirable to derive an error formula for the relatively simple case where $\psi_1$, $\psi_2$ and $\psi_3$ are regarded as the variables; and for this, the first step is to obtain the total differentials of $\phi$ and $\delta$.

From

$$\tan \phi = -\frac{\cos \alpha}{\cos \beta},$$

we have

$$\tan \phi = -\frac{\begin{vmatrix} \sin \psi_1 & \cos \beta_1 & \cos \gamma_1 \\ \sin \psi_2 & \cos \beta_2 & \cos \gamma_2 \\ \sin \psi_3 & \cos \beta_3 & \cos \gamma_3 \end{vmatrix}}{\begin{vmatrix} \cos \alpha_1 & \sin \psi_1 & \cos \gamma_1 \\ \cos \alpha_2 & \sin \psi_2 & \cos \gamma_2 \\ \cos \alpha_3 & \sin \psi_3 & \cos \gamma_3 \end{vmatrix}} = -\frac{D_1}{D_2}.$$

Differentiating, we have

$$\sec^2 \phi d\phi = \frac{D_1 dD_2 - D_2 dD_1}{D_2^2}$$

$$d\phi = \frac{D_1 dD_2 - D_2 dD_1}{D_2^2 \sec^2 \phi}$$

$$dD_2 = \begin{vmatrix} \cos \alpha_1 & \cos \psi_1 d\psi_1 & \cos \gamma_1 \\ \cos \alpha_2 & \cos \psi_2 d\psi_2 & \cos \gamma_2 \\ \cos \alpha_3 & \cos \psi_3 d\psi_3 & \cos \gamma_3 \end{vmatrix}$$

$$D_1 dD_2 = \begin{vmatrix} \sin \psi_1 \cos \alpha_1 + \cos \beta_1 \cos \alpha_2 + \cos \gamma_1 \cos \alpha_3 \\ \sin \psi_2 \cos \alpha_1 + \cos \beta_2 \cos \alpha_2 + \cos \gamma_2 \cos \alpha_3 \\ \sin \psi_3 \cos \alpha_1 + \cos \beta_3 \cos \alpha_2 + \cos \gamma_3 \cos \alpha_3 \end{vmatrix}$$

$$\begin{vmatrix} \sin \psi_1 \cos \psi_1 d\psi_1 + \cos \beta_1 \cos \psi_2 d\psi_2 + \cos \gamma_1 \cos \psi_3 d\psi_3 \\ \sin \psi_2 \cos \psi_1 d\psi_1 + \cos \beta_2 \cos \psi_2 d\psi_2 + \cos \gamma_2 \cos \psi_3 d\psi_3 \\ \sin \psi_3 \cos \psi_1 d\psi_1 + \cos \beta_3 \cos \psi_2 d\psi_2 + \cos \gamma_3 \cos \psi_3 d\psi_3 \end{vmatrix}$$

$$\begin{vmatrix} \sin \psi_1 \cos \gamma_1 + \cos \beta_1 \cos \gamma_2 + \cos \gamma_1 \cos \gamma_3 \\ \sin \psi_2 \cos \gamma_1 + \cos \beta_2 \cos \gamma_2 + \cos \gamma_2 \cos \gamma_3 \\ \sin \psi_3 \cos \gamma_1 + \cos \beta_3 \cos \gamma_2 + \cos^2 \gamma_3 \end{vmatrix}$$

$$dD_1 = \begin{vmatrix} \cos \psi_1 d\psi_1 & \cos \beta_1 & \cos \gamma_1 \\ \cos \psi_2 d\psi_2 & \cos \beta_2 & \cos \gamma_2 \\ \cos \psi_3 d\psi_3 & \cos \beta_3 & \cos \gamma_3 \end{vmatrix}$$

$$D_2dD_1 = \begin{vmatrix} \cos\alpha_1\cos\psi_1 d\psi_1 + \sin\psi_1\cos\psi_2 d\psi_2 + \cos\gamma_1\cos\psi_3 d\psi_3 \\ \cos\alpha_2\cos\psi_1 d\psi_1 + \sin\psi_2\cos\psi_2 d\psi_2 + \cos\gamma_2\cos\psi_3 d\psi_3 \\ \cos\alpha_3\cos\psi_1 d\psi_1 + \sin\psi_3\cos\psi_2 d\psi_2 + \cos\gamma_3\cos\psi_3 d\psi_3 \end{vmatrix}$$

$$\begin{vmatrix} \cos\alpha_1\cos\beta_1 + \sin\psi_1\cos\beta_2 + \cos\gamma_1\cos\beta_3 \\ \cos\alpha_2\cos\beta_1 + \sin\psi_2\cos\beta_2 + \cos\gamma_2\cos\beta_3 \\ \cos\alpha_3\cos\beta_1 + \sin\psi_3\cos\beta_2 + \cos\gamma_3\cos\beta_3 \end{vmatrix}$$

$$\begin{vmatrix} \cos\alpha_1\cos\gamma_1 + \sin\psi_1\cos\gamma_2 + \cos\gamma_1\cos\gamma_3 \\ \cos\alpha_2\cos\gamma_1 + \sin\psi_2\cos\gamma_2 + \cos\gamma_2\cos\gamma_3 \\ \cos\alpha_3\cos\gamma_1 + \sin\psi_2\cos\gamma_2 + \cos^2\gamma_3 \end{vmatrix}$$

$$D_2^2 = \begin{vmatrix} \begin{vmatrix} \sin\psi_2 & \cos\gamma_2 \\ \sin\psi_3 & \cos\gamma_3 \end{vmatrix} & - \begin{vmatrix} \cos\alpha_2 & \cos\gamma_2 \\ \cos\alpha_3 & \cos\gamma_3 \end{vmatrix} & \begin{vmatrix} \cos\alpha_2 & \sin\psi_2 \\ \cos\alpha_3 & \sin\psi_3 \end{vmatrix} \\ - \begin{vmatrix} \sin\psi_1 & \cos\gamma_1 \\ \sin\psi_3 & \cos\gamma_3 \end{vmatrix} & \begin{vmatrix} \cos\alpha_1 & \cos\gamma_1 \\ \cos\alpha_3 & \cos\gamma_3 \end{vmatrix} & - \begin{vmatrix} \cos\alpha_1 & \sin\psi_1 \\ \cos\alpha_3 & \sin\psi_3 \end{vmatrix} \\ \begin{vmatrix} \sin\psi_1 & \cos\gamma_1 \\ \sin\psi_2 & \cos\gamma_2 \end{vmatrix} & - \begin{vmatrix} \cos\alpha_1 & \cos\gamma_1 \\ \cos\alpha_2 & \cos\gamma_2 \end{vmatrix} & \begin{vmatrix} \cos\alpha_1 & \sin\psi_1 \\ \cos\alpha_2 & \sin\psi_2 \end{vmatrix} \end{vmatrix}.$$

The maximum error in $\phi$ is

$$\frac{d\phi}{\phi} = \frac{D_1dD_2 - D_2dD_1}{\phi \cdot D_2^2 \sec^2\phi}$$

where $D_1dD_2$, $D_2dD_1$ and $D_2^2$ are replaced by the determinants above derived; and where the differentials $d\psi_1$, $d\psi_2$ and $d\psi_3$ are replaced by their corresponding increments.

In determining the error formula for the dip, we start with the following equation:

$$\cos\delta = \frac{\begin{vmatrix} \cos\alpha_1 & \cos\beta_1 & \sin\psi_1 \\ \cos\alpha_2 & \cos\beta_2 & \sin\psi_2 \\ \cos\alpha_3 & \cos\beta_3 & \sin\psi_3 \end{vmatrix}}{\begin{vmatrix} \cos\alpha_1 & \cos\beta_1 & \cos\gamma_1 \\ \cos\alpha_2 & \cos\beta_2 & \cos\gamma_2 \\ \cos\alpha_3 & \cos\beta_3 & \cos\gamma_3 \end{vmatrix}} = \frac{D_3}{D_4}.$$

Differentiating, we have

$$-\sin\delta d\delta = \frac{D_4 dD_3 - D_3 dD_4}{D_4^2}$$

$$d\delta = \frac{D_3 dD_4 - D_4 dD_3}{D_4^2 \sin\delta} = -\frac{dD_3}{D_4 \sin\delta}$$

$$dD_3 = \begin{vmatrix} \cos\alpha_1 & \cos\beta_1 & \cos\psi_1 d\psi_1 \\ \cos\alpha_2 & \cos\beta_2 & \cos\psi_2 d\psi_2 \\ \cos\alpha_3 & \cos\beta_3 & \cos\psi_3 d\psi_3 \end{vmatrix}.$$

The maximum error in $\delta$ is

$$\frac{d\delta}{\delta} = -\frac{dD_3}{\delta \cdot D_4 \sin\delta}$$

where $dD_3$ and $D_4$ are replaced by the determinants above derived; and where the differentials $d\psi_1$, $d\psi_2$ and $d\psi_3$ are replaced by their corresponding increments.

PROBLEM.

From a practical point of view, the following problem is not a typical one, at least in the field of sub-surface exploration, though it might possibly be regarded as such in the field of metal mining. This problem has really been selected, or rather envisaged, primarily to illustrate how the method is applied, when three drill holes are driven in different octants.

In the bottom of a valley, a drill hole is directed upward into the wall of the valley, at an angle of 10°, and in a direction N. 25° W. A second drill hole is directed downward at an angle of 60°, in a direction S. 70° W. A third drill hole is directed downward at an angle of 55°, in a direction S. 50° E. The angles between the axes of the drill cores and the stratigraphic or structural planes are respectively 30°, 45° and 5°. It is required to find the strike and dip of these planes, assuming that they are parallel.

The necessary data are as follows:

$$\cos\alpha_1 = \cos\theta_1 \cos\omega_1 = \cos 205° \cos 10° = -.89254$$
$$\cos\beta_1 = \sin\theta_1 \cos\omega_1 = \sin 205° \cos 10° = -.41620$$
$$\cos\gamma_1 = \cos(90° - \omega_1) = \cos(90° - 10°) = .17365$$

$$\begin{aligned}
\cos\alpha_2 &= \cos\theta_2\cos\omega_2 &&= \cos 290^\circ\cos(-60^\circ) &&= \phantom{-}.17101\\
\cos\beta_2 &= \sin\theta_2\cos\omega_2 &&= \sin 290^\circ\cos(-60^\circ) &&= -.46985\\
\cos\gamma_2 &= \cos(90^\circ-\omega_2) &&= \cos(90^\circ+60^\circ) &&= -.86603
\end{aligned}$$

$$\begin{aligned}
\cos\alpha_3 &= \cos\theta_3\cos\omega_3 &&= \cos 50^\circ\cos(-55^\circ) &&= \phantom{-}.36869\\
\cos\beta_3 &= \sin\theta_3\cos\omega_3 &&= \sin 50^\circ\cos(-55^\circ) &&= \phantom{-}.43938\\
\cos\gamma_3 &= \cos(90^\circ-\omega_3) &&= \cos(90^\circ+55^\circ) &&= -.81915
\end{aligned}$$

$$\begin{aligned}
\sin\psi_1 &= \sin 30^\circ = \phantom{-}.50000\\
\sin\psi_2 &= \sin 45^\circ = \phantom{-}.70711\\
\sin\psi_3 &= \sin\ 5^\circ = \phantom{-}.08716
\end{aligned}$$

$$\cos\alpha = \frac{\begin{vmatrix} .50000 & -.41620 & .17365\\ .70711 & -.46985 & -.86603\\ .08716 & .43938 & -.81915 \end{vmatrix}}{\begin{vmatrix} -.89254 & -.41620 & .17365\\ .17101 & -.46985 & -.86603\\ .36869 & .43938 & -.81915 \end{vmatrix}} = -\frac{.23410}{.56543} = -.41402$$

$$\cos\beta = \frac{\begin{vmatrix} -.89254 & .50000 & .17365\\ .17101 & .70711 & -.86603\\ .36869 & .08716 & -.81915 \end{vmatrix}}{D} = -\frac{.31733}{.56543} = -.56122$$

$$\cos\gamma = \frac{\begin{vmatrix} -.89254 & -.41620 & .50000\\ .17101 & -.46985 & .70711\\ .36869 & .43938 & .08716 \end{vmatrix}}{D} = -\frac{.33572}{.56543} = -.59374$$

$$\phi = \arctan\left[-\frac{.41402}{.56122}\right] = \arctan(-.73771) = 143^\circ\,35'$$

$$\delta = 53^\circ\,34.6'.$$

Hence the strike and dip are N. 36° E., 54° S.E.

The computation of the possible errors in $\phi$ and $\delta$, using the error formulæ above deduced, is a tedious and lengthy procedure. Four

involved determinants occur in the two formulæ, and each of these has to be evaluated four times, according to the algebraic signs given to the increments of $\psi_1$, $\psi_2$ and $\psi_3$. In this problem, it has been found that the greatest error in strike may accrue when $\pm \Delta\psi_1 = \mp \Delta\psi_2 = \pm \Delta\psi_3$; and the greatest error in dip may accrue when all three increments have the same algebraic sign. Assuming initial errors of 1° in the measurement of these three angles, the maximum errors in strike and dip are found to be approximately, and respectively, $2\frac{1}{3}$ and $3\frac{1}{2}$ per cents.

These percentages apply only to the specific problem that has been worked, and have no general meaning. If the possible error in similar problems is required, it will have to be computed. In assuming initial errors of 1° in $\psi_1$, $\psi_2$ and $\psi_3$, it was not meant to imply that these angles could be measured consistently to that degree of accuracy. Moreover, accentuated errors in these angles may occur as a result of deviations in the directions of the drill holes. But the errors that accrue from assuming initial errors of 1° show that initial errors several times as great may be present without invalidating the method. It must also be remembered that the core angles may be measured in multiple; and providing the drill holes are straight, a mean value of superior accuracy may thus be obtained for $\psi_1$, $\psi_2$ and $\psi_3$, that may approach or actually exceed the postulated accuracy in the initial measurements.

## CURVED SURFACES.

In the determination of the strike and dip of plane surfaces, two problems were mentioned; first, where the drill holes penetrated to some recognizable horizon, and second, where no such horizon could be recognized. The same two problems exist with regard to curved surfaces, but only the first of these is treated in this paper. The second problem could also be solved, but the analysis would involve a consideration of parallel surfaces, and would necessitate the formulation and solution of a series of differential equations. It is doubtful whether the results would be commensurate with the labor involved; and it is even more doubtful whether the solutions would be generally useful.

In the first of these two problems, the fundamental or given data are different from those heretofore used, because both the initial and end points of the drill holes, as well as their lengths, are required for the solution. The necessary data are the locations, in three-dimensional coordinates, of the initial and end points of nine drill holes, which penetrate to some recognizable stratum, and the method consists essentially in fitting the end points of these nine drill holes to some ternary quadric surface. Having obtained an algebraic expression for this surface, the equations of tangent planes can then be deduced at any of the nine end point stations, or at any other points on the stratigraphic surface, within the immediate vicinity of the drill holes.

It is apparent that such a solution is only an approximation to the truth, because the stratigraphic surface is not necessarily a quadric. But when one considers the variety of surfaces that are represented by the general equation of the second degree, it seems reasonable that one of these surfaces can be found which will represent with reasonable fidelity a stratigraphic surface, within the small limits considered. Such surfaces include spheres, cylinders, cones, ellipsoids, paraboloids and hyperboloids. However, if the problem appeared to justify still further refinement, and if the necessary data were available, the stratigraphic surface might be fitted to cubic, quartic or $n$-tic surfaces in three variables. But it should be mentioned that the utilization of cubic and quartic surfaces would require respectively 19 and 34 drill hole records; and the computations would be very laborious.

If the sites of the initial and end points of the drill holes are known, it is easy to compute the three-dimensional coordinates of each of the nine end points, referred to some arbitrarily chosen origin of coordinates. Hence we may consider as given a series of nine points $(x_1y_1z_1)$, $(x_2y_2z_2)$, $(x_3y_3z_3)$, etc., which lie upon the stratigraphic surface. Now the general equation of a ternary quadric is as follows:

$$ax^2 + by^2 + cz^2 + 2fxy + 2gyz + 2hzx + 2lx + 2my + 2nz + d = 0.$$

But the equation of the desired stratigraphic surface may also be

represented by the following determinant:

$$\begin{vmatrix} x^2 & y^2 & z^2 & xy & yz & zx & x & y & z & 1 \\ x_1^2 & y_1^2 & z_1^2 & x_1y_1 & y_1z_1 & z_1x_1 & x_1 & y_1 & z_1 & 1 \\ x_2^2 & y_2^2 & z_2^2 & x_2y_2 & y_2z_2 & z_2x_2 & x_2 & y_2 & z_2 & 1 \\ \cdot & & & & & & & & & \\ \cdot & & & & & & & & & \\ \cdot & & & & & & & & & \\ \cdot & & & & & & & & & \\ \cdot & & & & & & & & & \\ \cdot & & & & & & & & & \\ x_9^2 & y_9^2 & z_9^2 & x_9y_9 & y_9z_9 & z_9x_9 & x_9 & y_9 & z_9 & 1 \end{vmatrix} = 0.$$

Expanded in minors, a series of cofactors can be found for $x^2$, $y^2$, $z^2$, etc.; and these cofactors will necessarily be the coefficients $a$, $b$, $c$, $d$, etc., of the general equation of the quadric. Hence these coefficients are solved in terms of the following determinants:

$$\begin{aligned} a &= \begin{vmatrix} y_1^2 & z_2^2 & x_3y_3 & y_4z_4 & z_5x_5 & x_6 & y_7 & z_8 & 1 \end{vmatrix} \\ b &= -\begin{vmatrix} x_1^2 & z_2^2 & x_3y_3 & y_4z_4 & z_5x_5 & x_6 & y_7 & z_8 & 1 \end{vmatrix} \\ c &= \begin{vmatrix} x_1^2 & y_2^2 & x_3y_3 & y_4z_4 & z_5x_5 & x_6 & y_7 & z_8 & 1 \end{vmatrix} \\ 2f &= -\begin{vmatrix} x_1^2 & y_2^2 & z_3^2 & y_4z_4 & z_5x_5 & x_6 & y_7 & z_8 & 1 \end{vmatrix} \\ 2g &= \begin{vmatrix} x_1^2 & y_2^2 & z_3^2 & x_4y_4 & z_5x_5 & x_6 & y_7 & z_8 & 1 \end{vmatrix} \\ 2h &= -\begin{vmatrix} x_1^2 & y_2^2 & z_3^2 & x_4y_4 & y_5z_5 & x_6 & y_7 & z_8 & 1 \end{vmatrix} \\ 2l &= \begin{vmatrix} x_1^2 & y_2^2 & z_3^2 & x_4y_4 & y_5z_5 & z_6x_6 & y_7 & z_8 & 1 \end{vmatrix} \\ 2m &= -\begin{vmatrix} x_1^2 & y_2^2 & z_3^2 & x_4y_4 & y_5z_5 & z_6x_6 & x_7 & z_8 & 1 \end{vmatrix} \\ 2n &= \begin{vmatrix} x_1^2 & y_2^2 & z_3^2 & x_4y_4 & y_5z_5 & z_6x_6 & x_7 & y_8 & 1 \end{vmatrix}. \end{aligned}$$

Now the equation of a tangent to any surface may be written as:

$$\left(\frac{\partial F}{\partial x}\right)_0 (x - x_0) + \left(\frac{\partial F}{\partial y}\right)_0 (y - y_0) + \left(\frac{\partial F}{\partial z}\right)_0 (z - z_0) = 0$$

$$\left(\frac{\partial F}{\partial x}\right)_0 = 2ax_0 + 2fy_0 + 2hz_0 + 2l$$

$$\left(\frac{\partial F}{\partial y}\right)_0 = 2by_0 + 2fx_0 + 2gz_0 + 2m$$

$$\left(\frac{\partial F}{\partial z}\right)_0 = 2cz_0 + 2gy_0 + 2hx_0 + 2n.$$

The equation of the tangent to the quadric is then found to be:

$$(ax_0 + fy_0 + hz_0 + l)(x - x_0) + (by_0 + fx_0 + gz_0 + m)(y - y_0) + (cz_0 + gy_0 + hx_0 + n)(z - z_0) = 0.$$

Expanding this equation, and combining it with the equation

$$-(ax_0^2 + by_0^2 + cz_0^2) = 2fx_0y_0 + 2gy_0z_0 + 2hz_0x_0 + 2lx_0 + 2my_0 + 2nz_0 + d,$$

we find the general equation of the tangent to a ternary quadric to be:

$$(ax_0 + fy_0 + hz_0 + l)x + (fx_0 + by_0 + gz_0 + m)y + (hx_0 + gy_0 + cz_0 + n)z - (lx_0 + my_0 + nz_0) = 0.$$

The coefficients of $x$, $y$ and $z$ in this equation, hereafter designated as $A$, $B$ and $C$, are the direction components, and not the direction cosines, of the normal to the tangent to the stratigraphic plane. But as the direction components are proportional to the direction cosines, this makes no difference in the computation of the strike. Hence we have

$$\phi = \text{arc tan}\left[-\frac{ax_0 + fy_0 + hz_0 + l}{fx_0 + by_0 + gz_0 + m}\right].$$

For the computation of the dip, however, the value of $\cos\gamma$ must first be obtained; and this is done by means of the following equation:

$$\cos\gamma = \frac{C}{\sqrt{A^2 + B^2 + C^2}}.$$

Thereafter the magnitude and direction of the dip are obtained in the manner heretofore described.

The solutions by this method depend upon the evaluation of nine numerical determinants of the ninth order. To attempt this directly, by their expansion into minors, would result in the development of 544,320 determinants of the third order, each of which would have to be evaluated; and this is obviously quite impractical. Fortunately, it is true that the value of a determinant is unaltered if to each element of one row (or column) there is added a constant multiplier of the corresponding element of another row (or column).

By means of this theorem, all but one of the minors may be made to vanish, so that a determinant of the ninth order may be condensed into an expression having the form of

$$D = F_1 \cdot F_2 \cdot F_3 \cdot F_4 \cdot F_5 \cdot F_6 \cdot F_7 \begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix}.$$

Another method of accomplishing the same result is by the utilization of the Chiò condensation method, as explained by Aitken.[4]

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
*January 18, 1943.*

[4] Aitken, A. C.: Determinants and Matrices, 2nd Edit. Edinburgh, 1942, pp. 45–48.

# PARAGENESIS OF THE ORE OF THE NORMETAL MINE, ABITIBI COUNTY, QUEBEC.

HENRY M. PUTMAN.

ABSTRACT.

Four waves of mineralization are shown: first: abundant pyrite replacement of the wall rock; second: pyrrhotite mineralization; third: quartz-sphalerite-chalcopyrite wave; fourth: a minor marcasite-galena mineralization. There is a marked discontinuity between the first and the second waves and clear overlap of the second and third waves.

## INTRODUCTION.

THE Normetal Mine is located in the North part of Desmeloizes township in the Western Quebec mining area. It has been described under the original name of "Abana Mines" by J. B. Mawdsley.[1] A recent description of the area has been given by C. Tolman.[2]

The mine occupies sheared zones in Keewatin volcanics and sediments intruded by acidic dikes. All the samples described were taken from orebodies 1 and 2 that have been found to extend into each other at depth.[3] The main mineralization is pyrite, pyrrhotite, chalcopyrite, and sphalerite. Geological occurrence and mineralization are similar to those of the Horne Mine, the Aldermac Mine, and the Waite-Amulet Mine, three other important copper-zinc producers of Western Quebec.[4]

[1] Mawdsley, J. B.: Desmeloizes area, Abitibi district, Quebec. Canada Geol. Surv., Summ. Rep., 1928, Part C: 28–83, 1930.

[2] Tolman, C.: Preliminary report on Normetal Mine area, Abitibi County. Quebec Bur. Mines, Prelim. Rep. 170, 1942.

[3] Tolman, C.: op. cit., p. 9.

[4] For description of those deposits and the geology refer to: Price, P.: The geology and ore deposits of the Horne Mine, Noranda, Quebec. Ph.D. thesis, McGill University, 1933. Cooke, H. C., James, W. F., and Mawdsley, J. B.: Geology and ore deposits of Rouyn-Harricanaw regions, Quebec. Canada Geol. Surv., Mem. 165, 1931.

The present work presents the study of typical specimens given by the Normetal Mining Corporation to Laval University. The main problem was to determine the paragenesis of the ore minerals. Five types of mineral associations can be clearly distinguished among the specimens. They are:

I, the zinc ore type;
II, the chlorite-copper ore type;
III, the quartz copper ore type;
IV, the zinc-copper ore type;
V, the pyrite type.

However, it is to be noted that these types may grade into each other but the above classification has been found the most representative and the most convenient.

## MINERALOGRAPHY.

### *Zinc Ore Type.*

*Hand Specimens.* The body of the specimens is medium-grained specular sphalerite, purplish black in color. Small irregular spots of chalcopyrite are dispersed in the sphalerite mass. There is a small amount of gangue which is mostly quartz. A few flakes of chlorite show a zonal disposition with some chalcopyrite spots. Some specimens show thin bands (1 to 3 mm thick) of very fine-grained pyrite.

*Polished Surfaces.* Sphalerite forms the matrix of the specimens and fine polishing shows that it crystallized in medium irregular crystals and polysynthetic twins (Fig. 1). Quartz is

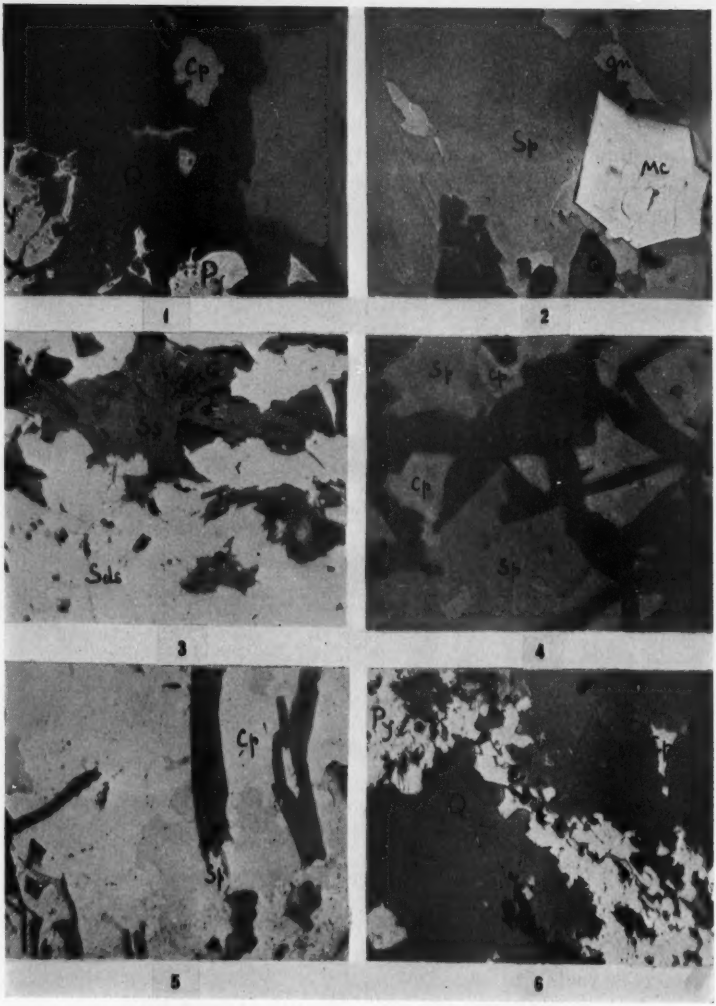
FIG. 1. Pyrite (Py) replaced by quartz (Q) and sphalerite (Sp), chalcopyrite (Cp) inclusions in the quartz. Twin lamellae in sphalerite. × 158.

FIG. 2. Cockscomb form of marcasite (Mc) in a zone of sphalerite (Sp) rich in galena (Gn). Some quartz (Q). × 158.

FIG. 3. Relation of quartz (Q), soft silicate gangue (Ss) and sulphides (Sds). Quartz crack filled with chalcopyrite. × 158.

FIGS. 4 AND 5. Typical relations of chalcopyrite (Cp) sphalerite (Sp) and late silicate gangue (LS). × 158.

FIG. 6. Quartz (Q) replacing pyrite (Py); chalcopyrite (Cp) inclusions in the quartz. × 158.




FIGS. 1–6.

relatively abundant, occurring as medium irregular grains, whose boundaries suggest weak replacement by sphalerite. Chalcopyrite occurs in small spots in the quartz and in the sphalerite and clearly replaces those two minerals. Pyrite occurs sparsely and is strongly replaced by quartz and sphalerite (Fig. 1). Sometimes replacement is carried on along crystallographic planes, leaving as remnants false idiomorphic crystals (Fig. 12). Galena is not abundant but is widely distributed as very small to small spots replacing sphalerite along small veins and dotted lines. Certain zones of galena are related to marcasite, which occurs as small to medium idiomorphic crystals, often twins (Fig. 2).

The sequence in the specimens is: pyrite largely earliest, then quartz-sphalerite-chalcopyrite mineralization, lastly galena-marcasite mineralization.

### *Chlorite Copper Ore Type.*

*Hand Specimens.* Specimens grade from poorly mineralized chlorite to massive chalcopyrite. For the latter specimens, chalcopyrite is the matrix of sheets of chlorite, bands (about 1 mm thick) of pyrrhotite and disseminated minor gangue in zones along schistosity.

*Polished Surfaces.* The matrix of the specimens is chalcopyrite, which crystallized in medium irregular crystals and more rarely in polysynthetic twins (Fig. 9). Pyrrhotite occurs as

FIG. 7. Pyrite (Py) cracks invaded by chalcopyrite (Cp) and quartz (Q). × 158.

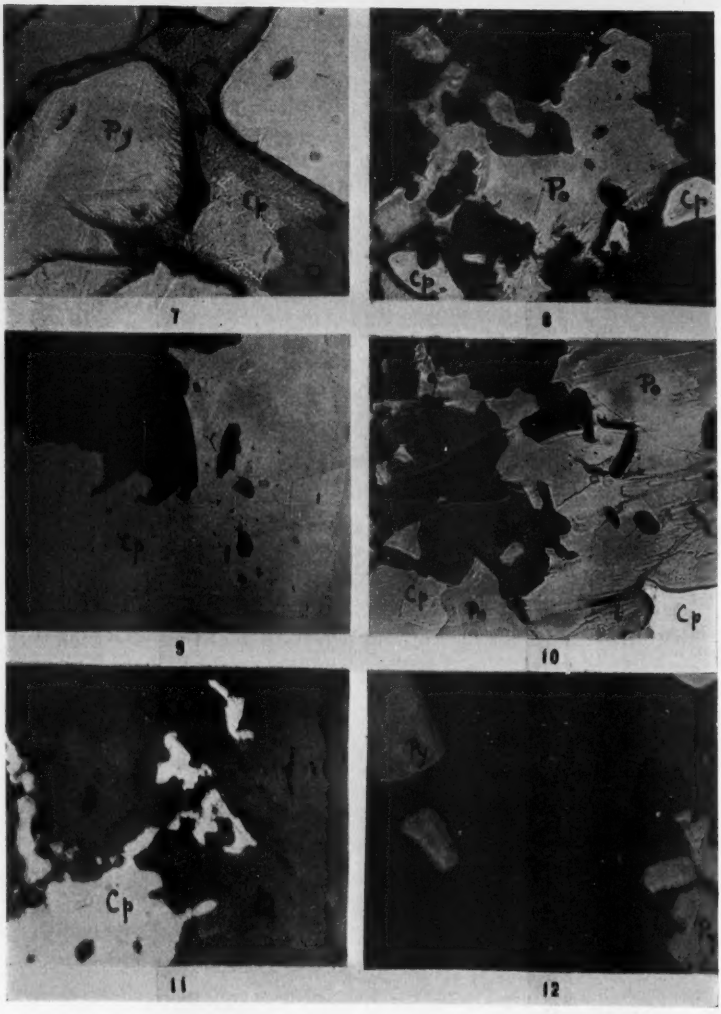
FIG. 8. Pyrrhotite (Po) with sphalerite (Sp) and chalcopyrite (Cp). Intermixture of remnant gangue and late silicate. Quartz with chalcopyrite inclusions. × 158.

FIG. 9. Crystallization of chalcopyrite (Cp) shown: polysynthetic twins and medium crystals. Late silicate (LS), intermixture of quartz and late silicate (Im). × 158.

FIG. 10. Pyrrhotite (Po) replaced by sphalerite (Sp). Some late silicate (LS) cutting the whole mass. × 158.

FIG. 11. Chalcopyrite (Cp) replacing quartz (Q). × 158.

FIG. 12. Sphalerite and quartz replacing pyrite. False idiomorphic crystals of pyrite. × 158.




FIGS. 7–12.

small rounded disseminated grains and as medium elongated grains in certain zones; in the latter case it is highly penetrated by chalcopyrite and sphalerite (Fig. 10). Quartz is abundant as subangular medium grains. It shows replacement by chalcopyrite (Fig. 3), and forms at places a close intermixture with a late silicate (Fig. 9). Sphalerite occurs generally either in relation to the late silicate, to pyrrhotite or to quartz, also as small spots in chalcopyrite variable in abundance with the specimens. In one area a fine regular intergrowth of sphalerite and quartz has been observed. Sphalerite replaces pyrrhotite (Fig. 10) and may also occur as inclusion in it.

Remnant chlorite gangue occurs as earthy masses. Soft silicate prismatic laths are abundant and cut every other mineral in the specimens (Figs. 4 and 5). When the specimen is cut partly in an important chlorite inclusion the difference between the remnant chlorite and the late silicate is well shown at the boundary of the inclusion. The chlorite is earthy and the late silicate projects itself from the chlorite in the chalcopyrite as smooth prismatic laths. The close connection of the late silicate with remnant chlorite and with quartz (Fig. 3) suggests that it has been formed at a late or secondary stage of the silicification that accompanies the chalcopyrite-sphalerite mineralization. It is probably to be considered as the metamorphosed initial constituent of schist that has recrystallized with, or after, the chalcopyrite mineralization.

Pyrite occurs in variable quantities and is the earliest mineral, replaced mainly by quartz (Fig. 6) and chalcopyrite. In many specimens pyrite remnant grains are scattered along a few schistosity lines. The general disposition of the pyrite suggests an early replacement of the schist by pyrite along schistosity, followed by a replacement by chalcopyrite in the same way.

Magnetite occurs very scarcely as small elongated crystals in the gangue, suggesting pseudomorphism of hematite.

The sequence shown by the specimens is: pyrite earliest, then pyrrhotite, followed by quartz-chalcopyrite-sphalerite mineralization, finally soft silicate.

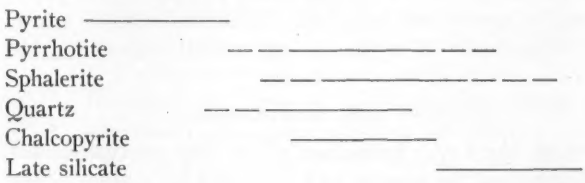
*Quartz Copper Ore Type.*

*Hand Specimens.* The specimens consist of quartz with remnant sheets of chlorite and irregular chalcopyrite along schistosity.

*Polished Surfaces.* The matrix of the specimens is quartz. Remnant deformed laths of gangue are abundant, forming bands and ribbons in the direction of the schistosity. These bands sometimes include very small crystals of pyrite. In most cases gangue silicate is idiomorphic, suggesting that it is not the original mineral but a product of metamorphism. Chalcopyrite is the most abundant sulphide and clearly replaces quartz. It invades the latter mineral along veinlike and irregular projecting areas (Fig. 11). Pyrrhotite and sphalerite are not abundant and are replaced by chalcopyrite.

Pyrite occurs as very small crystals in the gangue but also as medium rounded crystals in the chalcopyrite. These are frequently cracked and cracks are filled with chalcopyrite.

The paragenesis is as follows:




*Zinc-Copper Ore Type.*

*Hand Specimens.* The specimens are composed of fine-crumpled bands and intermixtures of chalcopyrite, pyrite, sphalerite, quartz, and gray gangue.

*Polished Surfaces.* The surfaces show a chalcopyrite sphalerite quartz and pyrrhotite mixture filling cracks and intergranular spaces in pyrite (Fig. 7) and also replacing an early gangue mineral (Fig. 8). Chalcopyrite, sphalerite and quartz in about equal amounts do not show clear cut relations between each other. Pyrrhotite is more sparsely distributed and its very irregular

boundaries with chalcopyrite give good criteria of replacement by this latter mineral. A late silicate at places forms an intermixture with a remnant gangue (Fig. 9).

The tabulation of the paragenesis is given below:

Pyrite ————————
Pyrrhotite ————————
Chalcopyrite ————————
Sphalerite ————————
Quartz ————————
Late silicate ————————

*Pyrite Type.*

*Hand Specimens.* The specimens consist of a very fine-grained pyrite which shows some brecciation and porosity. Pyrite is altered to limonite along small breccia cavities. Some quartz spots replace the pyrite.

*Polished Surfaces.* In some specimens the polished surface shows many cracks and pits in the pyrite mostly filled by quartz. In others the surface shows residual pyrite invaded by two kinds of gangue, by quartz with sphalerite inclusions, and by a soft silicate. Replacement of pyrite by quartz and sphalerite is obvious.

## SUMMARY AND CONCLUSIONS.

*Texture of the Ore.* Formation of the ore by replacement along schistosity of the country rocks is a striking feature of the ore examined. Crumpled bands and ribbon-like textures are common. Brecciation seems to be a specific character of the pyrite. Porosity is well developed in some pyrite specimens and has been observed in sphalerite and gangue. All the minerals are generally fine- to medium-grained.

*Ore Minerals.* The following minerals have been observed: pyrite, pyrrhotite, marcasite, magnetite, chalcopyrite, sphalerite, and galena. Among them pyrite, chalcopyrite, and sphalerite are the most abundant. Marcasite was observed in one specimen only and magnetite also. Mawdsley [5] has observed enargite in

[5] Mawdsley, J. B.: op. cit., p. 70c, 1930.

sphalerite, associated with galena and containing blebs of chalcopyrite, but that mineral has not been seen in the specimen described here.

*Gangue Minerals.* Three gangue minerals are very abundant: foliated chlorite as a remnant mineral, anhedral quartz introduced with the ore minerals, and a soft silicate in euhedral laths presumably due to metamorphism of the chlorite.

*Mineral Relations.* Pyrite occurs either alone in masses, or disseminated in the other sulphides. Pyrrhotite occurs disseminated in the chalcopyrite-sphalerite ore. Marcasite was found associated with sphalerite and galena. Magnetite was found in very small amounts with gangue. Chalcopyrite, sphalerite, and quartz form the body of the ore and occur generally in close association although in variable proportions. The composite mass is often cut by a late soft silicate. Galena occurs as inclusions in sphalerite and when marcasite is present it is associated with that mineral.

*Paragenesis.* Four waves of mineralization are clearly shown:

*Largely first:* abundant pyrite replacement of the wall rock.

*Second:* pyrrhotite mineralization.

*Third and most important:* quartz-sphalerite-chalcopyrite wave.

*Fourth:* a minor marcasite-galena mineralization.

*At a last stage:* formation of an idiomorphic silicate, presumably by secondary metamorphic effects of silicification.

There is a marked discontinuity between the first and the second waves, clear overlap of the second and the third waves and presumable overlap of the third and fourth waves.

The general sequence can be tabulated as follows:

Price [6] gives the following paragenesis for the ore of the Horne Mine, 53 miles south of Normetal Mine: pyrite, magnetite, pyrrhotite, sphalerite, chalcopyrite, and it can be seen that this order is the same as the above.

A paragenesis based on a study by the writer of 26 ore specimens from the Aldermac Mine, 54 miles south of Normetal Mine, is exactly the same as that of the Normetal (with the exception of galena and marcasite, which minerals have not been observed in the specimens).

The sequence shown by investigation of 8 ore specimens from the Waite-Amulet deposit, 47 miles south of Normetal Mine, is also the same for pyrite, quartz, sphalerite, chalcopyrite, galena, and late silicate; but there are presumably two generations of pyrrhotite in that deposit: one between pyrite and quartz depositions and the other between chalcopyrite and galena.

In a general manner the paragenesis reinforces the similarity of the four above mentioned deposits.

ACKNOWLEDGMENTS.

The present work has been carried out under the supervision of Professor G. M. Schwartz. I wish to express to him my gratefulness for his teaching, advice, and help.

Messrs. D. S. Morton and D. E. Bourke, of the Normetal Corporation, have presented Laval University with the specimens described herein.

The laboratory work was done in the research laboratories of Laval University.

QUEBEC, P. Q., CANADA,
*Dec. 15, 1942.*

[6] Price, P.: op. cit., pp. 260, 261, 262.

# DISCUSSION AND COMMUNICATIONS

## THE WORK OF GEOLOGISTS ON WATER SUPPLIES FOR WAR PURPOSES.[1]

The extensive and effective service which the geologists trained in hydrology are rendering to this country in the prosecution of the war is a matter of great satisfaction. Most of this service is, of course, being rendered by geologists of the Geological Survey, United States Department of the Interior, but much is also being done by geologists in the State Surveys, the Army Engineers, universities, etc.

The leadership in the civilian work was taken by David G. Thompson, up to the time of his serious illness, and he brought to it not only his 25 years of groundwater investigation but also his valuable experience with similar problems in the first world war. From the beginning of the emergency we recognized the necessity of making many contacts with the Army, Navy, Office of Production Management, War Production Board, and other Federal agencies, and with the consulting engineers and contractors on the Federal jobs; and of rendering prompt and practical service to all these agencies. The magnitude of this service is indicated by the fact that in the 1942 fiscal year the Geological Survey made reports on groundwater at about 900 places for Army and Navy establishments and war industries. Practically all of these reports involved geology. In the Southwestern Division of the Army Engineers there is now a definite arrangement whereby the Geological Survey, under the leadership of W. N. White, advises on the water supply problems of the Army establishments and obtains their well

[1] Published by permission of the Director, Geological Survey, U. S. Dept. of the Interior.

data for study and preservation. Work has also been done by civilian geologists on water supplies for war needs in foreign countries, including field work in the Latin American countries, the West Indies, and the islands of the Pacific.

Early in the emergency, Lieut. Col. George H. Taylor, who is an engineer by training but also, in fact, a geologist, was transferred to the Army Engineers and assigned to Washington to act as liaison officer between the Army and the Geological Survey in matters concerning water supply, and to prepare a section on groundwater for the Army water supply manual and to help select well drilling equipment for overseas use. In this capacity he has functioned effectively in addition to the performance of other important duties.

In response to specific requests from the Army, a total of ten geologists from the Geological Survey have thus far been commissioned for service with respect to the development of groundwater supplies. Several of these are attached to general staffs of overseas armies or have special assignments; the rest are officers in water supply battalions, the general plan being to have one geologist on the official staff of each water supply battalion. Several of these geologists are now with the troops in different parts of the world and the others are with units that are being trained for overseas service.

The first of these geologists to enter the military service was Major R. C. Cady, who went overseas about a year ago and who was engaged in locating well sites for water supplies for military operations in Africa and Asia until his death on January 15, 1943, as a result of accidental injuries. The other geologists are as follows: Captains R. M. Leggette and H. E. Thomas, and Lieutenants F. C. Foley, R. L. Nace, R. C. Newcomb, S. L. Schoff, R. C. Baker, Bernard Fisher, and W. C. Rasmussen.

It is known that some of these men were effective in the development of water supplies for the troops immediately after their landing in North Africa, by driving and drilling wells.

O. E. MEINZER.

*February 5, 1943.*

## SUGGESTED USE OF THE WORD MICROFACIES.

*Sir:* Articles dealing with microscopic phases of petrology, petrography and economic geology seem to me unduly burdened with such trite and cumbersome phrases as "In thin section the rock is seen to be composed of"; "Under the microscope the mineral shows"; "As seen under the microscope the rock consists of."

I suggest the word microfacies in suitable forms to express these ideas. Thus, "The rock has the microfacial characteristics of a devitrified tuff," or "In microfacies the rock is an altered quartz monzonite"; "Microfacially the feldspar shows albite twinning."

JOHN S. BROWN.

BALMAT, NEW YORK,
*Aug. 17, 1942.*

# REVIEWS *

**Structural Geology.** By MARLAND P. BILLINGS. Pp. 473; Figs. 336; Pls. 19. Prentice-Hall, Inc., New York, 1942. Price, $4.50.

This new presentation of structural geology is not "just another book" that serves up the usual subject matter in warmed-over fashion, with slight changes in seasoning. Much of the material presented has not appeared in competing textbooks. The style is refreshingly direct and vigorous, and the text is supplemented by well executed diagrams which keep before the student the necessity of three-dimensional thinking. Special commendation is due the author for his decision to restrict the treatment to "the study of relatively local structural units," and to omit both the details of experimental studies and the elusive viewpoints of megatectonics. Students should be well grounded in the demonstrable principles and the ordinary techniques of the subject before they venture into vague frontiers where even the more experienced can lose their bearings.

Unusual aspects of the book are suggested by titles of several chapters; *e.g.*, "Plutons," "Extrusive Igneous Rocks," "Structural Petrology," "Geophysical Methods." Some of these topics of course appear in other books, but in the present volume they receive rather full and adequate treatment. Probably the author's field experience, especially in New Hampshire, emphasized in his mind the structural as well as the petrologic aspects of igneous bodies. Principles and techniques used in petrofabric study, both megascopic and microscopic, receive clear general explanation, not with the idea of equipping students adequately in this difficult branch of geology, but in the conviction that every student should appreciate its importance and possibilities. Similarly, the several common techniques used in geophysical prospecting are explained in their relation to geologic structure, without any thought of introducing students to the highly technical instruments and methods employed in this field for trained specialists. Modern application of structural geology extends beyond the zone of observation to concealed features, and every geologist should have some appreciation of methods that are available for solving field problems.

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

Block diagrams are used to advantage throughout the book, and the elements of folds are particularly well illustrated by three-dimensional diagrams. Billings has adopted a useful distinction, made by only a few other authors, between the terms *pitch* and *plunge* in relation to fold axes and other linear structural elements. These terms, commonly used as synonyms, can and should be employed for two distinct relationships, both important. Exercises in a special section at the end of the book are well designed to prepare the student for practical problems such as he will probably meet in the field. Some of these exercises "have teeth"; they call for concentrated effort and some ingenuity, and they bring realization that structural geology involves quantitative engineering methods. Some of the exercises are laid out on perforated sheets which can be torn out of the book for submission to the instructor. This arrangement is unfortunate in one respect: removal of a sheet takes away the entire basis of the exercise concerned, and leaves the book to that extent incomplete.

The book contains some errors and infelicities. For example the Lake Basin en échelon faults in Montana are described, by text and by diagram, as "northwesterly trending faults," and are explained as resulting from a couple, "the northerly block moving east . . ." (pp. 194–195). A discussion of the strain ellipsoid (p. 108) states that conjugate shear fractures, experimentally produced, intersect at acute angles and do not correspond to theoretical planes of no distortion. On later pages, however—*e.g.*, in Fig. 180, A, p. 216—shear fractures are represented as "essentially parallel" to theoretical planes that intersect at angles strongly obtuse. Students are mystified by the selective orientation of the strain ellipse illustrated by comparison of Figs. 183 and 192, and wonder what the orientation would be in the latter diagram for fractures near the axial plane of the fold. Unfortunate confusion results from the representation in a unit block, Fig. 187, of dynamic conditions that are incompatible among themselves.

The reviewer is not in sympathy with some parts of the fault nomenclature adopted in the book. Billings recognizes both descriptive and genetic terms, but by preference he divides dip-slip faults into *gravity* and *thrust* faults. A gravity fault is defined as one "along which the hanging wall has moved down relative to the footwall." The term *normal* fault is widely used in this sense; but Billings restricts the terms *normal* and *reverse* to indicate apparent relative movements, whatever the actual relative movement may have been. In practise these distinctions become academic. Many geologists indicate presumed dip-slip movement by the terms normal and reverse; if there is direct evidence of strike-slip, these geologists speak of a *strike-slip* fault, regardless of geometric relations among beds or other features affected. Billings tacitly recognizes this

common usage by the title of his Chapter 11: "Gravity or Normal Faults." If the two terms are interchangeable, why not use *normal,* and avoid the implication, which lurks persistently in spite of printed definitions, that the hanging wall of every such fault has actually moved downward in response to gravity? If this origin could be demonstrated generally, the term *gravity fault* would be justified as part of a truly genetic classification. However if we except local "landslide" faults, and certain other faults in special geologic settings, it must be admitted that the exact role played by gravity in causing movement on faults is difficult to establish. On the other hand it is conceivable that differential forces responsible for plateau uplift may set up shearing stresses that result in large normal faults, along which the footwall blocks move to higher elevation than the adjacent hanging wall blocks. Under the assumed conditions gravity has no part in the faulting—except to resist the uplifting forces.

If one general class of dip-slip faults is to be called *normal,* the other class should be called *reverse,* since the two terms are paired by long usage. Why should we have the synonymous term *thrust* for this second general class? This term is already usefully employed by many geologists, to designate low-angle reverse faults with large heave. Billings, following time-honored precedent, calls such faults *overthrusts.* When the Committee on Nomenclature of Faults, reporting thirty years ago, pronounced in favor of this descriptive term, the vigorous controversy on underthrusting versus overthrusting had not developed. One member of that committee, A. C. Lawson, who has been also a prominent proponent of underthrusting, probably would now accept the noncommittal term *thrust.* W. B. Scott has used the term consistently, in place of *overthrust,* since the first appearance of his textbook in 1897.

A more vigorous protest is in order against the attention given to numerous "species" of thrusts, each designated by name. Billings retains a classification that has met some acceptance, and adds two or three terms of his own. Students come to have an anxious concern that each thrust must conform to one of these "types," according to an important structural principle; in general this is not true. To the reviewer the most objectionable of the terms used in the classification is *shear* thrust. Since all thrusts are conspicuously the creatures of shearing stress, it seems as incongruous to have a subclass called "shear thrusts" as it would be to select a limited number of horses to be known as "quadrupedal horses." One thrust studied by the reviewer may be used to illustrate any one of several so-called "types," depending on the part of the fault selected. At one locality it is a typical "initial shear thrust"; a mile distant along the strike its relation to the deformed strata make it a "break thrust"; farther down the dip it is revealed as a great "bedding thrust" or "strip thrust";

several miles forward the plate overrode the land surface—as all extensive thrust masses must have done—and there it corresponds to Billings' definition of an "erosion thrust." Shall we hyphenate all of these terms, in an attempt to label the fault properly? Adequate information about such a structural feature can be given only by describing it fully.

This matter of terminology is after all a minor issue in the volume under discussion. The foregoing outburst reveals a conviction on the part of the reviewer that our nomenclature of faults needs simplification, and is not intended as carping criticism of a book which in most respects is a sound and useful aid in teaching.

CHESTER R. LONGWELL.

**Map Interpretation with Military Applications.** By WILLIAM C. PUTNAM. Pp. viii + 67; Figs. 26; Pls. X. McGraw-Hill Company, Inc., New York, 1943. Price, $1.25.

Here is a timely book to provide a background for understanding the significance of the landscape as it is represented on maps and aerial photographs. It may well become one of the most important texts to be used in the coming days by those universities and colleges which have been selected to carry out the Army and Navy educational programs, as well as in the many officers' training schools of all services.

The author, at present making terrain studies for the Military Geology Unit of the U. S. Geological Survey, makes no pretense at completely covering the field in his little volume. He treats briefly of the elemental problems of contour maps: representative fractions and graphic scales, direction and declination, cultural features, what contours are, profiles, gradients, road and railroad layouts, visibility profiles and location by resection and triangle of error then goes on to give the elements of aerial photographic interpretation. A brief chapter on geologic interpretation serves as an essential foundation for the most important chapter of the book, from a tactical point of view: Erosive Processes. In this well-knit chapter the importance of streams, deltas, deserts, shore processes, coastlines and glaciation to tactical maneuvers is clearly stated and well illustrated with maps, drawings, block diagrams and photographs.

Perhaps the most valuable part of the book to anyone faced with setting up a course in the use of maps and photographs in wartime is the excellent listing of selected references, including a well-thought-out list of the best illustrative maps and charts.

LT. BERNARR BATES, U. S. N. R.
NAVAL AIR COMBAT INTELLIGENCE OFFICERS' SCHOOL.

**Fundamentals of Economic Geography, Rev. Edit.** By N. A. BENGSTON and W. VAN ROYEN. Pp. xxvii + 802; Figs. 300. Prentice-Hall, New York, 1942. Price, $5.00; special to colleges, $4.25.

This is a revised edition of the textbook first published in 1935. New statistical material and illustrations showing the latest pre-war trends of production, and many text sections, rewritten in relation to problems confronting the world at war, have brought it up-to-date. The authors believe that "by developing a general understanding of the importance of material resources, climatic and other geographic conditions in waging war, a sound basis also can be laid for the construction of an enduring peace." They have therefore stressed the distribution of the world's basic resources.

Since the book is an introductory text it covers, briefly, a great deal of material and considers the earth itself; the distribution of population and interrelationships of the environment and the needs and activities of populations; minerals of economic use and the metal industries; power utilization and resources; the various climates of the world and the economic products of each; agricultural industries; economic significance of the sea; and manufactures and commerce. A final chapter on the changing world makes a plea for intelligent trade conditions.

**Commodity Year Book.** The Commodity Research Bureau, New York, 1942. 2 Vols. Master Edition, Pp. 413, Price, $7.50; Commodity Statistics, Pp. 204, Price, $5.00; Both volumes, $10.00.

In 1939 the Commodity Research Bureau, Inc., published the first Commodity Year book which incorporated brief discussions of processing and marketing with statistical tables of many basic commodities that make up the national economy. The Year book has been published annually. This fourth edition has been separated into two volumes of which Commodity Statistics brings up-to-date the previously published tables but contains no descriptive material. Certain information could not be made available with the country at war but insofar as possible the statistical data is complete.

The Master Edition of the Year book is an encyclopedia of factual data on 836 basic commodities, from acacia to zirconium, with detailed information on sources, uses, substitutes, importance in the war effort, etc. Many sections contain interesting descriptive material; some are even amusing, for instance that on pork. There are particularly valuable discussions on synthetic rubber and on plastics.

The editorial board as the result of the research concludes that "despite rationing and the diversion of many commodities from normal consuming channels, the United States is adequately equipped with raw material supplies for full military demands and the maintenance of the civilian economy."

## BOOKS RECEIVED.

RALPH E. DIGMAN.

**An Outline of Geography.** P. E. JAMES. Pp. xvi + 475; Figs. 182; Pls. 24. Ginn and Co., New York, 1943. Price, $3.75.

**Minerals and Rocks.** R. D. GEORGE. Pp. xviii + 595; Figs. 150; Pls. 48. D. Appleton-Century Co., New York, 1943. Price, $6.00.

**Geomorphology.** N. E. A. HINDS. Pp. xi + 894; Figs. 764. Prentice-Hall Inc., New York, 1943. Price, $5.00.

**American Philosophical Society Year Book 1942.** Pp. 398. The American Philosophical Society, Philadelphia, 1943.

**Outline Geologic Map of California Showing Locations of Tungsten Properties.** O. P. JENKINS. Economic Mineral Map of California, No. 4. California Division of Mines, San Francisco, 1942. Size 36″ × 42″, scale 1″ = 16 miles. *Includes a discussion of the geological aspect of occurrence and origin of tungsten and list of uses, list of properties, graphs of world production, California production, United States consumption, mineral production of California, tungsten production by states, and sketch figures of typical contact-metamorphic deposit of scheelite and of the geologic events of California.*

**U. S. Bureau of Mines, Washington, 1942.** Technical Papers.

No. 647. **Production of Industrial Explosives in the U. S. During 1941.** W. W. ADAMS AND V. E. WRENN. Pp. 30; Figs. 2. Price, 10 cents.

No. 648. **Mineral Matter in Coal.** G. C. SPRUNK AND H. J. O'DONNELL. Pp. 66; Figs. 48. Price, 15 cents.

No. 649. **Carbonizing Properties and Petrographic Composition of No. 2-Bed Coal From Bartoy Mine and No. 5-Bed Coal from Wilkeson-Miller Mine, Wilkeson, Pierce County, Washington.** J. D. DAVIS AND OTHERS. Pp. 46; Figs. 29. Price, 10 cents.

No. 651. **Coke-Oven Accidents in the U. S. During 1941.** W. W. ADAMS AND V. E. WRENN. Pp. 19; Figs. 3.

**Illinois Geological Survey, Urbana.**

**Geology and Mineral Resources of the Marseilles, Ottawa, and Streator Quadrangles.** H. B. WILLMAN AND J. N. PAYNE. Pp. 377; Figs. 127; Pls. 30. Bull. 66, 1942.

**Secondary Recovery of Oil in Illinois.** A. H. BELL, F. SQUIRES, AND G. V. COHEE. Pp. 14; Figs. 3. Press Bull. 43, 1943.

**Occurrence and Stratigraphic Distribution of Paleozoic Ostracodes.** C. L. COOPER. Pp. 13; Figs. 9. Rept. of Investigations No. 83, 1942.

**Differential Thermal Analyses of Clay Minerals and Other Hydrous Materials.** R. E. GRIM AND R. A. ROWLAND. Pp. 35; Figs. 14. Rept. of Investigations No. 85, 1942.

**Pennsylvania Fusulinidae of Illinois.** C. O. DUNBAR, L. G. HENBEST AND J. M. WELLER. Pp. 218; Figs. 14; Pls. 23. Bull. 67, 1942. *Contains columnar sections of Pennsylvanian formations showing stratigraphic distribution of fusulines. Exhaustive bibliography of the Fusulinidae and a check list of genera and species should be of great value.*

**Scott County.** H. R. BERGQUIST AND T. E. MCCUTCHEON. Pp. 282; Figs. 23; Pls. 11; Maps, 2. Mississippi Geol. Surv. Bull. 49. University, 1942.

**Report of Proceedings and Recommendations.** A. K. SNELGROVE, Edit. Pp. 21. Upper Peninsula of Michigan Mineral Industries Conference, Houghton, 1942.

**Oregon Dept. of Geol., Portland.**

**An Investigation of the Reported Occurrence of Tin at Juniper Ridge, Oregon.** H. C. HARRISON. Pp. 52; Pls. 4. Bull. 23, 1942. Price, 40 cents.

**Origin of the Black Sands of the Coast of Southwest Oregon.** W. H. TWENHOFEL. Pp. 25; Figs. 6; Pl. 1. Bull. 24, 1943. Price, 30 cents.

**Third Biennial Report of the State Department of Geology and Mineral Industries.** January, 1941 to July, 1942. Pp. 36. Bull. 25, 1942.

**Some Manganese Deposits in the Southern Oregon Coastal Region.** RANDALL E. BROWN. Pp. 6; Pls. 2. Geol. and Min. Indus. Short Pap. 9, 1942. Price, 10 cents.

**Tyrell Manganese Deposits and Other Similar Properties in the Lake Creek District, Oregon.** WALLACE D. LOWRY. Pp. 10; Figs. 3; Pls. 6. Geol. and Min. Indus. Short Pap. 10, 1943. Price, 15 cents.

**Biennial Report of the State Geologist.** H. A. BUEHLER. Pp. 80; Pls. 7. Missouri Geol. Surv. & Water Resources. Rolla, 1943.

Appendix I. **The Polo Gas Field.** F. C. GREENE AND H. S. MCQUEEN. Pp. 24; Pls. 5.

Appendix II. **Occurrence of Dolomite in the Fredericktown Area.** H. S. MCQUEEN. Pp. 16; Pls. 2.

Appendix III. **Occurrence of Bauxitic Clay in Stoddard County.** D. R. STEWART AND OTHERS. Pp. 21; Fig. 1; Pls. 7.

Appendix IV. **The Fortune, a new Devonian Formation.** J. G. GROHSKOPF AND OTHERS. Pp. 17; Fig. 1; Pls. 2.

Appendix V. **The Lexington Coal.** F. C. GREENE. Pp. 12; Fig. 1.

Appendix VI. **Manganese Deposits in Missouri.** O. R. GRAWE. Pp. 77; Figs. 3; Pls. 2.

**Forty-Fourth Annual Report of the Mining Industry of Idaho.** A. CAMPBELL. Pp. 233. Boise, 1942.

**The Mineral Industries of Arkansas in 1942.** R. J. ANDERSON. Pp. 170; Figs. 34. Arkansas Geol. Surv. Bull. 10. Little Rock, 1943.

**Pennsylvanian System in New Mexico.** M. L. THOMPSON. Pp. 91; Figs. 8; Pls. 2. Bureau of Mines and Mineral Resources Bull. 17. Socorro, 1942.

**The Oil and Gas Resources of New Mexico, Second Edit.** R. L. BATES. Pp. 319; Figs. 23; Pls. 25. Bureau of Mines and Mineral Resources Bull. 18. Socorro, 1942.

**Artvin bölgesi Kuvarshane bakir madenleri.** V. KOVENKO. Pp. 36; Figs. 9; Pls. 5. Extrait de "M.T.A." No. 2/27. Revue de l'Institut d'Etudes et de Recherches Minieres de Turquie. Ankara, 1942.

**Kansas Geol. Surv., Lawrence, 1942.** Bulletins.

41. Pt. 10. **Kansas Bentonite: Its Properties and Utilization.** E. D. KINNEY. Pp. 27; Fig. 1; Pls. 2.
43. **Geology and Ground-Water Resources of Ford County, Kansas.** H. A. WAITE. Pp. 244; Figs. 22; Pls. 16.
44. **Geophysical Investigations in the Tri-State Zinc and Lead Mining District.** J. J. JAKOSKY, R. M. DREYER, AND C. H. WILSON. Pp. 150; Figs. 55; Pls. 2; Tables 17. *A report of results of recent geophysical investigations of the Tri-State district.*
45. **Geology and Ground-Water Resources of Mead County, Kansas.** JOHN C. FRYE. Pp. 147; Figs. 13; Pls. 12.

**Report of the State Geologist, 1942–1943.** JOHN M. TREFETHEN. Pp. 36; Figs. 6. Maine Geol. Surv., Orono, 1943.

**Canada Dept. Mines and Resources.** Geol. Surv. Paper 42, Ottawa, 1942. *Recent maps of the series of Canadian geologic maps.* Price, 10 cents each.

42–7. **Takla, British Columbia.** J. E. ARMSTRONG. Prelim. map.
42–12. **Vassan-Dubuisson, Abitibi County, Quebec.** G. W. H. NORMAN. Prelim. map.
42–13. **Beresford Lake, Manitoba.** C. H. STOCKWELL. Prelim. map.

**Report of the Dept. of Mines and Resources Including Report of Soldier Settlement of Canada.** For Fiscal Year Ended March 31, 1942. Pp. 192. Price, 50 cents.

**Esquisse Géologique de L'Amérique du Nord.** M. DANLOUX-DUMESNILS. Pp. 30; Figs. 2. Ecole D'Ingénieurs. Montreal, 1942.

**Bibliography of Seismology.** E. A. HODGSON. Pp. 14. Pub. of the Dominion Observatory, Vol. 13, No. 12. Ottawa, Canada, 1943. Price, 25 cents.

**Instituto de Fisiografia y Geol. Rosario, Argentina.**

Pub. 11. **A Proposito de los Generos Plohophorus, Nopachthus y Panochthus.** A. CASTELLANOS. Pp. 74; Figs. 71. 1941.
Pub. C–1941. **Cronica Bibliografica.** A. CASTELLANOS AND P. PASOTTI. Pp. 75. 1941.
Pub. 12. **Sarmeintita, Un Nuevo Mineral de la Argentina.** V. ANGELELLI AND S. G. GORDON. Pp. 22; Figs. 11. 1942.
Pub. 13. **Los Sedimentos Prepampeanos del Valle de Nono, Argentina.** A. CASTELLANOS. Pp. 62; Figs. 48. 1942.

**Geologia de la Region Comprendida Entre Boca-Chica y La Puerta y Estudio de los Yacimientos Minerales de Santa Isabel, Estados Aragua y Guarico.** V. M. LOPEZ. Pp. 32; Figs. 17. Boletin de la Academia de Ciencias Fisicas, Matematicas y Naturales, Ano IX, Tomo VII, No. 22. Caracas, Venezuela, 1942.

# SCIENTIFIC NOTES AND NEWS

In reply to the letter from Ernest E. Fairbanks, printed on page 267 of the May number of the Journal, Prof. W. L. Whitehead of the Massachusetts Institute of Technology has submitted the following communication:

Sir: In a letter to ECONOMIC GEOLOGY Ernest E. Fairbanks discusses the source of a published error in the area of the Dracut norite stock.[1] The area stated to be "27 square miles," instead of about 9 square miles, is incorrect not, as Mr. Fairbanks suggests, on account of reproduction of his map, but from use of the mistaken numeral in the text of his paper of 1927.

Referring to the map in Dennen's paper, Fairbanks says, "I would have appreciated credit for same." This map, however, is not a copy of Fairbanks' map. On it are corrected various small mistakes in the earlier mapped outlines of the norite stock. The writer was in the field with Dennen and is assured not only that his map is based on original observations, but that the contacts illustrated by him are correct.

It is unfortunate that only general reference was made by Dennen to Fairbanks' paper and that authority for the area of the stock was not specifically cited. I regret that Mr. Fairbanks has made the suggestion to which I have replied, but feel that Mr. Dennen, who is now in the Marine Corps, should be exonerated.

W. C. MENDENHALL, director of the U. S. Geological Survey since 1931, has retired after nearly half a century with the Survey. W. E. WRATHER has been appointed to replace Mr. Mendenhall.

O. E. MEINZER, geologist in charge of the Division of Ground Water, Water Resources Branch of the U. S. Geological Survey, was recently awarded the fifth William Bowie medal for advancement of cooperative research in geophysics. The medal, awarded yearly by the American Geophysical Union, acknowledges the lifetime contribution of the recipient to geophysics, rather than a particular contribution during the year of the award.

J. B. LUCKE, head of the department of geology at the University of Connecticut, has been granted a leave of absence to accept a commission as lieutenant (jg) in the U. S. Naval Reserve.

DOUGLAS JOHNSON, professor of physiography at Columbia University, has been named Newberry professor.

J. B. TYRRELL has been elected an Honorary Member of the Royal Canadian Institute.

R. T. CHAMBERLIN, professor of geology at the University of Chicago, was elected to the American Philosophical Society at the annual meeting in Philadelphia in April.

[1] Dennen, W. H.: ECON. GEOL. 38: 26, 1943.